



Advanced Modular Power Approach to Affordable, Supportable Space Systems

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Prepared for the
Space 2012 Conference and Exposition
sponsored by the American Institute of Aeronautics and Astronautics
Pasadena, California, September 11–13, 2012

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Acknowledgments

The authors wish to thank the following for their support, insight and contribution to the paper. Robert Button of Energy Systems Branch for his technical guidance and paper review. Advanced Modular Power Systems (AMPS) Project Managers, David Imies and Ralph Jansen for project leadership. Study Team Leads, Raymond Beach, and James Soeder of Power Systems Branch for study guidance and power system insights. Monica Guzik, Brianne Scheidegger, Ken Burke, and Ian Jakupca for information on Non-Flow Through Fuel Cell technology. Bob Scheidegger of Solar Electric Propulsion, and Patrick George of Deep Space Habitat for vehicle power information. Mike Gernhardt, Joyce Seriale-Grush of Johnson Space Center (JSC) for Multi-Mission Space Exploration Vehicle information and insight.

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Abstract

Recent studies of missions to the Moon, Mars and Near Earth Asteroids (NEA) indicate that these missions often involve several distinct separately launched vehicles that must ultimately be integrated together in-flight and operate as one unit. Therefore, it is important to see these vehicles as elements of a larger segmented spacecraft rather than separate spacecraft flying in formation. The evolution of large multi-vehicle exploration architecture creates the need (and opportunity) to establish a global power architecture that is common across all vehicles. The Advanced Exploration Systems (AES) Modular Power System (AMPS) project managed by NASA Glenn Research Center (GRC) is aimed at establishing the modular power system architecture that will enable power systems to be built from a common set of modular building blocks. The project is developing, demonstrating and evaluating key modular power technologies that are expected to minimize non-recurring development costs, reduce recurring integration costs, as well as, mission operational and support costs. Further, modular power is expected to enhance mission flexibility, vehicle reliability, scalability and overall mission supportability. The AMPS project not only supports multi-vehicle architectures but should enable multi-mission capability as well. The AMPS technology development involves near term demonstrations involving developmental prototype vehicles and field demonstrations. These operational demonstrations not only serve as a means of evaluating modular technology but also provide feedback to developers that assure that they progress toward truly flexible and operationally supportable modular power architecture.

1.0 Introduction

Under the Advanced Exploration Systems (AES) Modular Power Systems (AMPS) project lead by NASA Glenn Research Center (GRC) the goal is to develop a modular power architecture composed of technologies for power generation, energy storage, power distribution and health management that will reduce the cost of future space systems.

The AMPS modular approach is intended to assure that the development and qualification investment is preserved in modular building blocks that have space qualified heritage while still providing adaptability to serve an array of future applications. This requires that the modular power development look across a broad array of vehicles and establish a common architecture that can be scaled to meet widely varying power needs. A modular approach can reduce power system integration complexity and costs by reducing the number of distinct integration steps and reduce the complexity of external equipment. Standardized modules may encapsulate a common set of reusable software, embedded diagnostics, health management functions and features that assure interoperability. A modular power system can enable the integrator to use a common set of standardized integration procedures, common set of tools, and a highly simplified set of test equipment. Encapsulating these capabilities in power modules not only streamlines integration but also benefits the supportability of operational spacecraft.

Future exploration missions emphasize destinations well beyond low Earth orbit (LEO) involving long and complex operations with multiple vehicles, (Ref. 1) as shown in Figure 1. Extremely limited and costly launch capacity restricts logistics up-mass. Crew consumables dominate logistics mass capacity and the capacity for maintenance spares is extremely low. This drives the program to squeeze

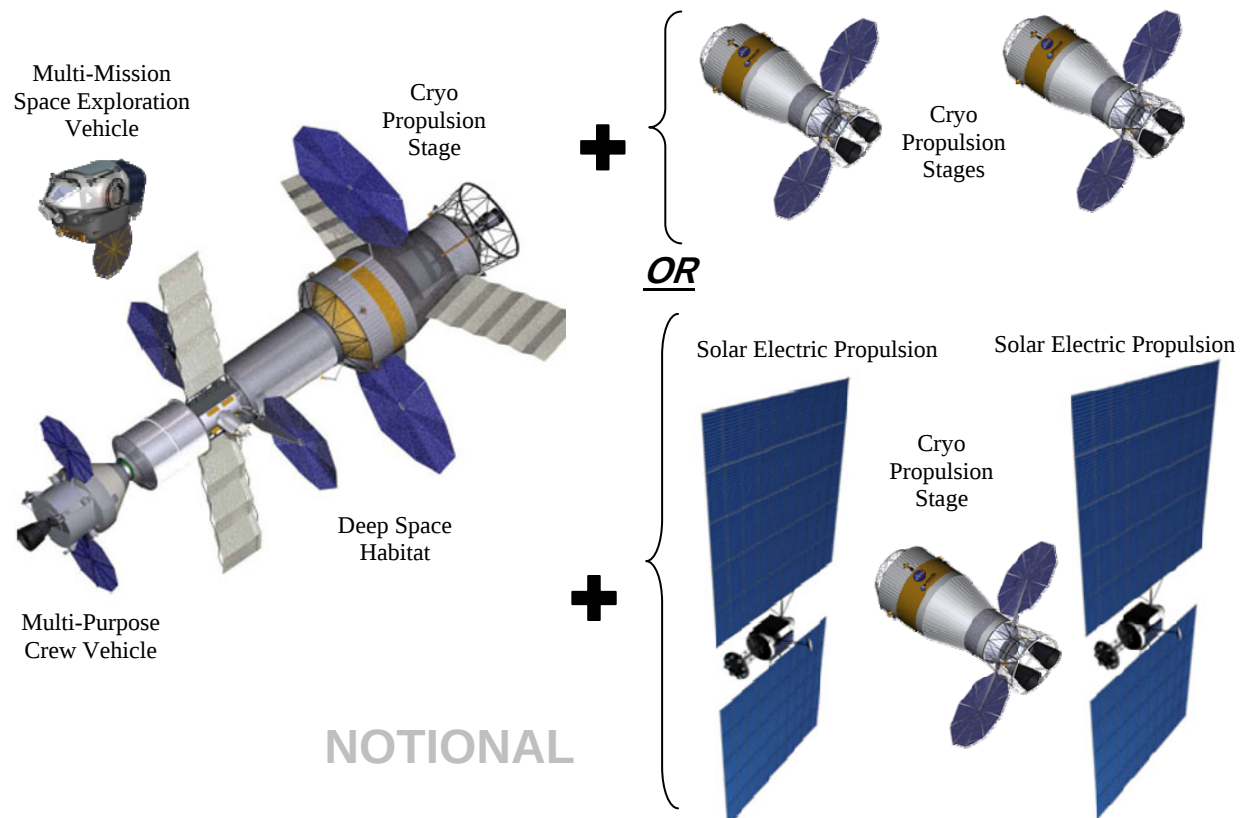


Figure 1.—Notional Multi-Vehicle stack for a near Earth asteroid mission. There are multiple crew vehicles and multiple propulsion schemes supporting asteroid missions. One mission scenario has 3 cryogenic propulsion stages while another has a mix of solar electric and cryogenic stages. This illustrates that there is an extraordinary amount of flight hardware and opportunities to exploit modular power.

service life out of every available piece of hardware. For the first time, hardware from vehicles that have completed their initial role and would normally be expended, are now considered a potential source of spares. The AMPS modular power strategy therefore includes the ability to salvage key elements to be reconfigured and repurposed for secondary applications including system spares (Ref. 2).

The following sections describe the AMPS project’s approach to overcome what have been barriers by developing modular power architecture, developing key modular power technologies and demonstrating them in user applications. AES Modular Power Systems approach can lead to a new set of legacy hardware that users can quickly adapt to new missions, drive down initial development cost, streamline prelaunch integration, reduce in-space support cost, and finally, enable the salvaging and repurposing of space flight hardware. In doing so, modular power not only preserves the utility and value of hardware, but enables the development and operation of multi-mission vehicles.

2.0 Defining Capabilities of Modular Power

AMPS capability objectives address the “abilities” that have long been goals of spacecraft designers. AMPS defines modular power features that provide commonality, but seeks to define an architecture that best supports the overall program by addressing scalability, flexibility, interoperability and supportability. In this section we define and discuss these abilities while staying alert to program and development pitfalls.

2.1 Commonality and Modularity Pitfalls

Modularity cannot be developed for commonality sake alone. There are number of pitfalls to avoid. Lessons learned in developing a new common standard include:

2.1.1 Poor Stakeholder Return on Investment

- A commonality standard limited to one specific project, (thus not truly common)
- One organization imposes its agenda on others (no mutual benefit)
- Added development complexity without downstream benefit
- Fixed or over constrained design that restricts options or suppresses innovation
- The new standard discards prior investments in established systems
- Unanticipated upfront cost of new processes, equipment, and staff retraining
- Incomplete development with end users expected to complete the development

2.1.2 Technical Penalties Due to Poorly Conceived Commonality Approach

- Increased mass or complexity with no compensating performance or cost gain
- Poor match with user needs
- Poor scalability and inflexible
- Partial solution, and lacking a complete overall architecture
- Prone to obsolescence by selecting proprietary solutions without industry buy in

2.1.3 Program Cost and Schedule Penalties Due to Poor Planning or Execution of Commonality

- Increased development time
- Developmental cost savings at the expense of operational and logistics costs
- Overestimating the benefit and underestimating the development cost
- Late introduction “the train has left the station”

The AMPS project proceeds with consideration of these lessons learned.

2.2 Commonality

Spacecraft power architecture with high commonality is built upon elements that use a common design approach and share common features to a point that hardware is interchangeable. For AMPS this common design approach extends to all spacecraft within the space exploration architecture. That is, power hardware can be interchangeable among a group of spacecraft. Commonality allows a program to pursue a single development effort that is then used by multiple spacecraft. This approach can save cost by eliminating the duplication among individual spacecraft development efforts. In some cases new standards can be developed to assure that spacecraft are compatible with the common power architecture. Commonality should not be imposed on spacecraft developers without first establishing the common power system needs and accommodating the variations from spacecraft to spacecraft. Commonality alone is insufficient; the approach to commonality must allow for scalability, flexibility, interoperability and operational supportability.

2.3 Scalable—Flexible Power

The modular power system architecture must accommodate the need for scalable and flexible power. Scalable power systems allow for an incremental expansion of capability. The International Space Station (ISS) Electric Power System was designed to be scalable at the system level since the ISS could not be built in a single mission. It was however important to establish electric power early and thus power systems were one of the first elements to arrive. Delivering power as parallel power channels allowed this

modest initial power capability to successfully expand over a series of missions. Scalable power capability will be needed as exploration missions extend beyond low Earth orbit.

Future exploration missions are expected to be very long and involve more complex operations involving multiple spacecraft. Further, these missions will not have the benefit of robust logistics infrastructure that ISS had (Ref. 3). A new generation of multi-mission exploration vehicles will perform multiple sorties with diverse objectives and durations. The flexibility to scale the power system up, or down, also enables the crew to tailor the capabilities to best match vehicle to the mission range, payload and environment. The modular flexibility enables the crew to select the best power generation, energy storage and power distribution options.

Scalability and flexibility is only feasible if it can be achieved without complex operations that require complex equipment, tools and extensive crew skills. Features that provide scalability and flexibility must be embedded into the design so that it does not need to be provided by additional external equipment.

2.4 Supportability

Supportability involves the operations, logistics and equipment required to maintain a system and assure a high degree of system availability (Ref. 4). The long term operational support of a space flight system has become an important program cost issue in an era of long lived space facilities, such as, the ISS. If supportability is not properly addressed, the crew and supporting ground operations may become burdened with system maintenance activity that competes with the science and mission objectives.

In long missions systems wear out or degrade over time and will require maintenance and hardware replacement. Upmass and crew time limitations mean that supportability cannot be achieved by simply “loading up” on spares and maintenance equipment. Supportability involves using operating techniques and technology that minimize the “logistics footprint” in terms of mass and operational crew time.

Supportability features are intended to maximize system availability while:

- Minimizing spares mass
- Minimizing maintenance equipment mass
- Minimizing operational time dedicated to maintenance
- Minimizing crew skill and training
- Enabling the crew to effectively and independently respond to problems

The supportability features that support these goals are also essential for effective modular commonality, scalability and flexibility. Supportability must be embedded into the modular design. Supportability is highly dependent on complete interoperability capabilities.

2.5 Interoperability

In general “Interoperability”, can be defined as a capability that allows multiple systems to connect and interact with minimum dependency on coordinating or integrating action by external systems or users. Ideally the connection and interaction is entirely transparent to the user (Ref. 5). When interoperability is extended to lower level modular hardware it enables portability and interchangeability. This form of interoperability is often referred to as “Plug-and-Play”.

For a long life program, interoperability can provide adaptability to long term change. In some cases interoperability is achieved by encapsulating hardware behind interface converters that, in effect, provide a high degree of “virtual” commonality. This adaptability enables systems to operate with low cost “legacy” hardware (Ref. 6). This adaptability tolerates diverse system components, mitigates the impact of obsolescence and holds open the path to future upgrades.

Interoperability involves a combination of hardware and software that is applied to all systems across multiple vehicles and permeates through all levels of the system. Interoperability is dependent on “smart” network capable modules connecting to “self-organizing” networks. For data and control the smart transducer standards, developed under IEEE 1451, provide the guidance for plug-and-play capability (Ref. 7). Modular power may need to establish additional standards for power interoperability. Power system interoperability standards may be extracted from the nation’s investment in “smart grid” technology.

3.0 Potential Affordability Aspects of Modular Power

AMPS anticipates a broad impact on program affordability by addressing non-recurring, recurring and long term operational costs.

3.1 Reducing Non-Recurring Costs

Reduction of the non-recurring development cost can be achieved by consolidating power system development across multiple vehicles. This is in contrast to designing and developing power system design unique to each vehicle. One way projects reduce development cost is to exploit existing designs with prior flight heritage or so called “legacy” hardware. This is rare for human spacecraft but common for satellites or robotic spacecraft. In fact, many NASA space science programs insist on showing flight heritage to reduce cost and minimize overall development and operational risk. Often the existing designs with heritage poorly match the new mission requirements and thus the new mission must compromise objectives or plan on extensive modification and requalification.

For AMPS the strategy is to develop a set of modular elements at varied scales that can be combined to provide the needed capability with a minimum excess. Designers can select from an assortment of modular building blocks and build a capability with the fewest number of blocks. As prequalified modules, the designers can acquire heritage while building the power architecture that matches their mission needs. Rather than simply impose modular and commonality standards, this approach is expected to provide spacecraft developers with an early incentive to adopt standardized units because of the inherent reduced risk and costs.

3.2 Reducing Recurring Costs of Integration

The recurring costs can be reduced by building systems from relatively low cost modular blocks where the tooling and fabrication costs are amortized over larger number production units. In comparison to large monolithic designs, smaller modules using readily available components are expected to be much less expensive, particularly, if production supports a number of vehicles. Recurring costs can be reduced by extending the commonality to the set of test and integration equipment that can support multiple vehicles. There is further recurring cost reduction if these are supported by standardized test and integration procedures.

3.3 Reducing Operational Life Cycle Costs

Modular power is expected to reduce operational cost by extending the useful life of spacecraft, minimizing the mass of spares, and simplifying maintenance operations. Replaceable modules called Orbital Replacement Units (ORU) have been successfully used to support the International Space Station.

Unlike ISS, however, the crew will not have easy access to Earth launched spare assemblies. All spares must be carried at initial launch. The ISS ORUs are relatively large and intended to support rapid replacement by humans or robots using simple tools and procedures. The intent was to make efficient use of crew time at the expense of mass. Long exploration missions cannot dedicate scarce logistics mass to oversized replacement units so repair must be performed at lower levels of assembly.

AMPS is working to modularize lower levels of assembly to reduce spares mass. The embedded health management diagnostics and prognostics capability will reduce the crew time required to isolate a fault. The plug and play interoperability provides self-test features that will assist in reintegrating the new module. This plug and play capability in combination with commonality allows multiple vehicles for a given mission to be serviced by a common set of spares. Further, modular commonality enables the practice of salvaging hardware from other vehicles, when needed, which further reduces spares mass.

Salvaging hardware can be used in extending the life of flight assets and enable a single vehicle to support multiple missions. Reusable spacecraft can potentially save billions of dollars in spacecraft value over the life of the program (Ref. 2).

4.0 Modularizing the Electric Power Systems

Space power systems are composed of power generation, energy storage and power distribution and management. Power generation includes solar arrays, fuel cells, and thermodynamic engines. Energy storage includes batteries but may include the evolving flywheel technology. Power distribution and management (PMAD) connects the power generation and energy storage to the user loads. It regulates the power and handles the delivery of power. It also provides the primary system fault detection, fault isolation and rerouting of power. These are typically designed as separate subsystems. The AMPS approach to modularity integrates certain PMAD regulator and health management functions into power generation and energy storage. Embedding these functions combined with plug-and-play features enables them to act as independent self-contained modular subsystems. This makes them more portable so they can be moved to different parts of the vehicle or another vehicle entirely.

There are a number of factors that will affect the effectiveness of the modular design. The ISS is the best example of spacecraft power with a high degree of modularity driven by scalability and supportability needs. It serves as an important point of departure for modular systems for missions beyond low Earth orbit. The ISS design incorporated modularity at various levels of assembly. For future missions, modularity and commonality needs to be driven down to lower levels of assembly.

4.1 Modularity Across Multiple Levels of Assembly

The AMPS project recognizes that modularity is not a new concept and has been used before but limited to higher levels of assembly. To minimize confusion project defines modularity at various levels of assembly is illustrated in Figure 2.

4.1.1 Modular Assembly

This level of hardware is commonly known as an ORU, which is the preferred level of replacement for ISS. It is a convenient scale for handling by humans or by robotics. As shown in Figure 3, ORUs are typically encapsulated in harden enclosures with mechanical and electrical interfaces intended to be easy to mated or de-mated by manual or robotic means.

4.1.2 Modular Subassembly

For power systems this subassembly level would mean circuit card within an ORU and are typically replaced by a ground based NASA Depots (Ref. 4). AMPS project seeks to modularize this level so that it can be handled as an in-space replaceable unit. There is a significant mass advantage as shown in Figure 3(b) (Ref. 8). ISS vintage systems were built around the parallel bus architectures and bus backplane drove host chassis size and, in turn, module volume and mass. Subassembly Modules can be packaged to be easy to replace with simple tools. This level is where significant commonality is found and also where elements are combined to configure the assembly level.

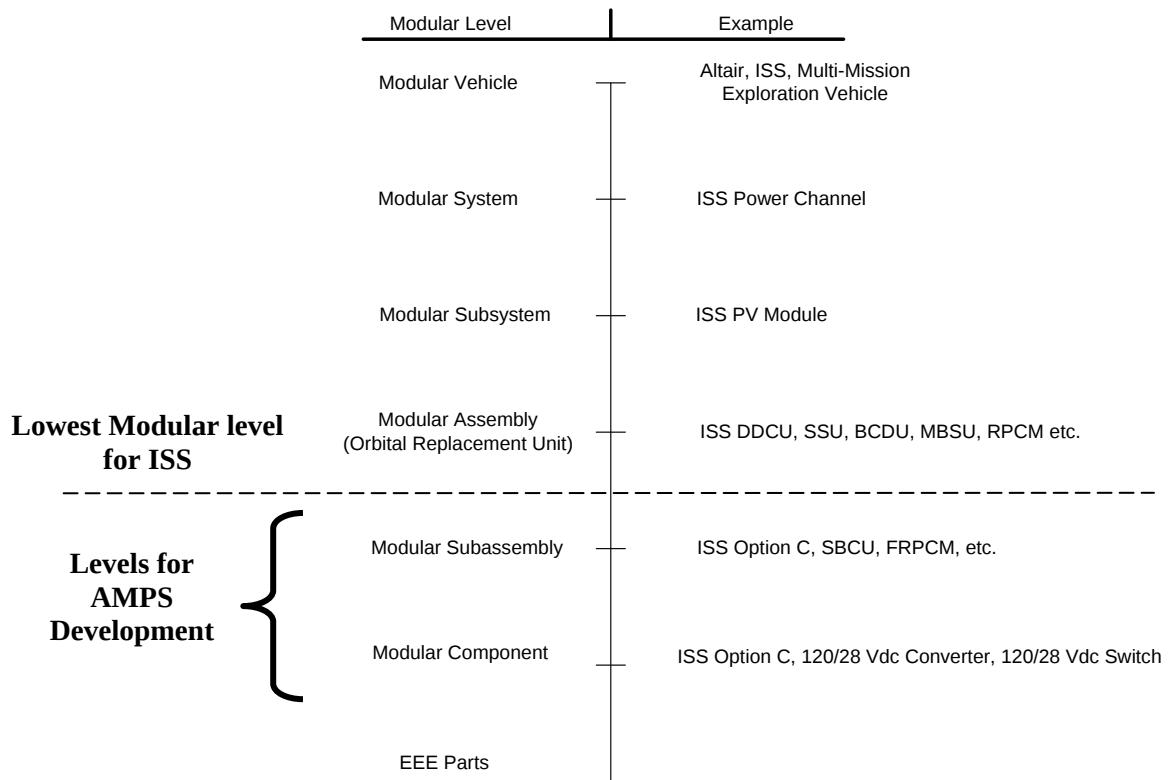


Figure 2.—Levels of Assembly for Modular Power Systems.

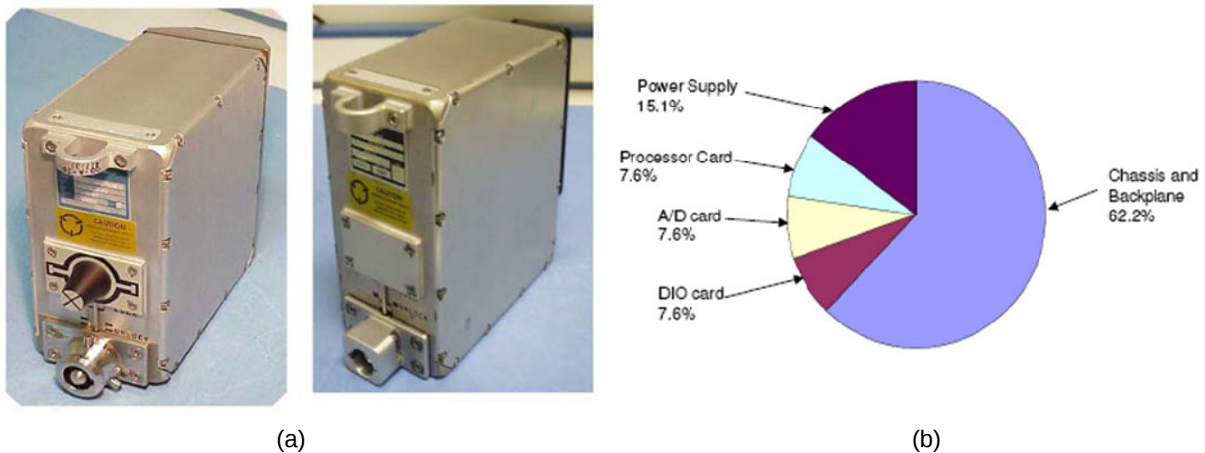


Figure 3.—ISS Assembly Level ORU. (a) The photos illustrate the common features of the Remote Power Controller Module (RPCM) units. The left RPCM is externally mounted and replaced by robotic means. The right unit is internally mounted and replaced manually. (NASA Photo), (b) The breakdown of an ORU often reveals that the chassis is the largest contributor to module mass and replacement of individual subassemblies is much more efficient (Ref. 8).

4.1.3 Modular Component

AMPS defines a Component Level Module as an encapsulated unit that cannot be further disassembled with common tools. This may be a single discrete part or a combination of multiple parts that are encapsulated in a manner that makes them a monolithic module. It is the lowest practical level for replaceable units that do not require special processing and equipment. The project may simplify the replacement process by using space qualified sockets instead of solder joints. The component level serves as the common fundamental power building block. A number of different functions can be provided by the electrical arrangement of these blocks. These blocks will incorporate sensors and other devices that support diagnostics but the diagnostics and health management functions will be handled at the next higher level.

4.2 Subassembly and Component Level Modularity Features

Driving modularity down to lower levels of assembly enables the designer to construct higher level assemblies with a common set of configurable building blocks. These lower level modules will incorporate features normally found in higher level assemblies.

4.2.4 Physical Encapsulation and Structure

Similar to high level modules, lower level modules should appear as physically independent encapsulated units. Where practical, modules will be designed to be self-contained and structured to be portable.

4.2.5 Functional and Software Encapsulation

The modules will have embedded functions and related software. The software may be microcontroller code or field programmable gate array firmware. This code may be modified to support reconfiguration or upgrades.

4.2.6 Independent Thermal Paths

Subassembly level modules may be configured in their own independent enclosure and may also provide its own thermal paths for removing heat.

4.2.7 Standardized Electrical Power Interfaces

Since many low level modules will be connected in series or parallel groups the module to module connections will be standardized.

4.2.8 Smart Network Capable Controllers

Subassembly modules will include “smart” network capable controllers (as defined in IEEE 1451) and will pass data over a network connection rather than a dedicated backplane (Ref. 7).

4.2.9 Embedded Health Management

The use of smart network capable controllers accommodates module related health management along with control and data functions. Most HM monitor existing control loops but other specialized sensors may be provided for added diagnostic and prognostic capability.

4.2.10 Embedded Supportability

Supportability functions work alongside control and HM functions. The primary purpose is to assist in the repair processes, and provide data that assist logistics and maintenance. Since modules may be moved from vehicle to vehicle they need to store their own configuration data and service history in an “electronic log book”. This enables the crew and ground support to interrogate the unit for its identity, its current configuration, maintenance status, service history and records of any anomalies. This also allows the crew to confirm that a module is the appropriate unit for its intended next application. It can also indicate how much remaining life is available based on operating experience.

4.3 Defining Modular Scaling Increments

Although the approach is to use modular blocks to build up power systems no one module size can be expected to meet the needs of all spacecraft. Using many small blocks means many interconnections and drives up the mass of harnessing while reducing overall reliability. Using large blocks means a tendency for overcapacity and excessive mass. An assortment of modular elements with varied capacity enables designers to mix and match modules to arrive at a system that meets mission needs.

For the AMPS project the generic term; “*scaling increment*” is defined here as the incremental capacity of a modular building block element. An assortment of several “scaling increments” may be needed to provide the flexibility to group elements together to meet the mission needs. Power generation, energy storage and power management will each have distinct scaling increments.

An example of the scaling increment can be found in the assorted sizes found in a standard electronic parts kit, E6 series resistors, for example, have a ± 20 percent tolerance and six distinct increments for every decade of value (10, 15, 22, 33, 47, 68) which allows the user to achieve any practical value between 10 and 100 with a series combination of just two units. The assortment is further reduced in the E3 series to only three values (10, 22, and 47) with ± 40 percent tolerance. Using the E3 series for power implies six increments to span vehicle power range from 1,000 to 100,000 W. This is a simplistic analogy and assumes that the design objective is to minimize the number of units. Other considerations, such as redundancy, may drive the design toward three or more units.

The scaling increments are dependent on other design factors, such as, redundancy requirements, thermal control requirements, mass of harnessing, and the practical limits of handling by crew or robotics. Each power subsystem will need to define its own scaling increment.

5.0 HAT Vehicle and Design Reference Mission

The AMPS project uses the vehicles from the Human Architecture Team (HAT) studies and their design reference missions (DRM) (Ref. 1). Each vehicle has a mix of common and unique mission power system requirements. At this stage the maturity, these requirements also change dramatically base on the specific DRM being studied. To assure that Module Power stays relevant to these missions some members of the AMPS project team also support the power system architecture development for HAT vehicles.

Examining the HAT DRMs, shown in Table 1, the vehicles tend to fall into a NEA Vehicle Group including Deep Space Habitat (DSH), Solar Electric Propulsion (SEP) vehicle, and Multi-Mission Space Exploration Vehicle (MMSEV-NEA). Otherwise they fall into a Lunar Vehicle Group that includes two variations of the Lunar Lander and a Multi-Mission Space Exploration Vehicle configured as a surface rover. Common to both vehicle groups is the Cryogenic Propulsion Stage (CPS) and thus shown as a “Common” vehicle. The study did not include the Space Launch System (SLS) or the Multi-Purpose Crew Vehicle (MPCV) because their development is more mature and will not be directly influenced by the AMPS technology development. The AMPS project will track these vehicles and develop, as needed, a suitable interface that assures interoperability with these legacy vehicles.

TABLE 1.—AMPS STUDY VEHICLES

Group	Near Earth Asteroids			Common	Lunar Surface Vehicles				
Vehicle	Deep Space Hab	Solar Electric Propulsion	Multi-Mission Space Exploration Vehicle	Cryo-Propulsion Stage	Multi-Mission Space Exploration Vehicle	Lunar Lander: Lunar Orbit Rendezvous		Lunar Lander: Earth Orbit Rendezvous	
DRM	NEA Transit & Proximity	NEA Transit	NEA Proximity	NEA & Lunar	Surface Rover	Descent Module	Ascent Module	Descent Module	Ascent Module

Note: Near Earth Asteroids are occasionally referred to as Near Earth Objects (NEO)

5.1 Cryogenic Propulsion Stage

The Cryogenic Propulsion Stage (CPS) appears in nearly all missions beyond LEO. In many cases multiple CPS units are used. CPS had a Block 1 and 2 variant. CPS Block 1 was a simple Cryo Stage operating on batteries. CPS Block 2 is configured for missions with long loiter periods (months). The substantial solar arrays capacity is needed to drive “zero-boil off” cryo-coolers to preserve propellants. CPS Block 2 is also used as a tanker or fuel depot to support NEA Missions. The study focused on CPS Block 2 for power requirements.

5.2 Deep Space Habitat

The Deep Space Habitat is the most complex system and may involve up to three distinct non-propulsive vehicle segments. DSH is also expected to acquire system heritage from the ISS. The DSH appears in nearly all NEA missions and serves as the habitat and core vehicle for the crew in transit and at the destination. It has substantial power needs. For long duration missions the main habitat is augmented by a node for attaching multiple vehicles including MMSEV. In addition, a logistics module is added to provide crew consumables, as well as, store vehicle spares. The DSH is considered the central hub for power system maintenance activity and spares.

5.3 Solar Electric Propulsion

Solar Electric Propulsion vehicle is unique since it has a power level exceeding 300 kW but is a relatively simple unmanned vehicle. As a low thrust high specific impulse vehicle, it’s primarily used well beyond low Earth orbit. In some scenarios, it is delivers to a CPS stage to L1 orbit. This vehicle has a split voltage system where 300 V is used as “direct drive” for the electric propulsion modules and 120 V is used for vehicle housekeeping.

5.4 Lunar Landers (Lunar Orbit and Earth Orbit Rendezvous)

For human missions lunar landers are actually composed of two modules. A Descent Module (DM) for landing and an Ascent Module (AM) that returns the crew to orbit. For uncrewed cargo missions the vehicle has only a Descent Module. There are two types Lunar Landers based on where the Multi-Purpose Crew Vehicle rendezvous with it which, in turn, drives the power configuration.

- Lunar Orbit Rendezvous (LOR) Lunar Lander is equipped with large solar arrays to power the cryo-coolers that preserve propellants during a long loiter period in Lunar Orbit.
- Earth Orbit Rendezvous (EOR) Lunar Lander is similar to Altair and thus has a very short loiter time. This vehicle taps the propellant supply for fuel cell generated power.
- Ascent Module (AM) The ascent module is very similar on both LOR and EOR Landers. The Descent Module powers Ascent Module when mated. After separation the independent Ascent Stage runs exclusively on batteries. The HAT studies show them as primary batteries however the long loiter times suggest that rechargeable secondary batteries may be more suitable.

5.5 Multi-Mission Space Exploration Vehicle: Near Earth Asteroid

The Multi Mission Space Exploration Vehicle (MMSEV) comes in two configurations. For the study it is treated as two distinct vehicles that have very different mission profiles and power requirements. The MMSEV NEA unit has a modular core habitable designed to support in-space missions. MMSEV NEA is a free flying vehicle for close-in exploration of asteroids. It maneuvers via a detachable propulsive module. It employs configurable detachable module called a PUP as a means of outfitting the vehicle for varied missions. This version of the MMSEV is expected to rely on solar arrays and batteries.

5.6 Multi-Mission Space Exploration Vehicle: Planetary Surface Rover

MMSEV Rover is a surface vehicle the maneuvers on a sophisticated wheeled mobility chassis. This version is a direct descendent of the Constellation Lunar Electric Rover (Ref. 9). Like the NEA version, the Rover version has a modular core habitat. The modular mobility chassis has six motor driven wheels assemblies that have independent steering and suspension height control that are all electrically driven. The high power demands of the mobility chassis require a 300 V power system in addition to the 120 V core. The MMSEV Rover may use either solar arrays or fuel cells. The rugged terrain and frequent shadowing limit the effectiveness of solar arrays. Further, because surface operations offer an opportunity to exploit in-situ resources, the unit is expected to use fuel cells when underway.

MMSEV appears to be most ideally suited for advanced modular power from the operational flexibility and configurability standpoint. Because MMSEV is conceived as a highly modular reconfigurable vehicle the MMSEV regarded as an important evaluation platform for modular power. Thus AMPS is supporting MMSEV ground demonstrations with advanced solar array, battery and fuel cell technologies.

5.7 Level 1 Power Requirements

Table 2 lists the top level requirements. Crew size and mission duration are key parameters that govern the size and performance of vehicle power systems. The maximum, nominal power requirements size the capacity of power generation, and power distribution. Energy storage is affected by the availability of solar power in insolation (daylight) periods and the duration of eclipse periods where batteries must bridge the gap. Fault tolerance levels also affect the series/parallel arrangement of modular power.

TABLE 2.—LEVEL 1 VEHICLE POWER REQUIREMENTS

Vehicle Grouping	NEAVehicles			Common	Lunar Vehicles				
Vehicle or Space Facility	Deep-Space Habitat	Solar Electric Propulsion	Multi-Mission Space Exploration Vehicle	Cryo Propulsion Stage	Multi-Mission Space Exploration Vehicle	Lunar Lander LOR Battery		Lunar Lander EOR (Altair) Fuel Cell	
Design Reference Mission	DSH at NEO	SEP NEO	MMSEV at NEO	NEO/LEO/HEO	Surface Rover	Descent Module	Ascent Module	Descent Module	Ascent Module
Level I Requirements									
Crew Capacity Maximum	4	N/A	4	N/A	0	4	4	4	0
Maximum Mission Days	365	676	7	14	TBD	7.5	7.5	21.7	0
Maximum [crew*days]	1640	676	28	N/A	TBD	DM: 4* 7 days, 6hrs	AM: 4 * 19 hrs	48.8	0
Total Maximum Power [kW]	20	320	3	25	10	7.9	0	7.1	3.1
Nominal power [kW]	15Kw - Nominal	N/A	tbd	23	3.5	DM: 4.7 kW	AM: 3.2 kW	4.5	2.9
Fall Safe Power [kW]	10kW for survival	See Total above	tbd	N/A	1.2	3.1 kW	0	N/A	N/A
Insolation [min]	240 (worst case)	0	0	56	0	71.3 min	0	none	none
Eclipse [min]	120 (worst case)	44.27 min	0	36	0	46.5 min	0	0	0

6.0 Modular Power Application Scenarios

To best understand how the modularity features assure flexibility, supportability and reusability we will step through operational scenarios. Operational scenarios help expose requirements and drive modular power features. Some features can be evaluated in operational field demonstrations.

6.1 In-Flight Reconfiguration Scenario

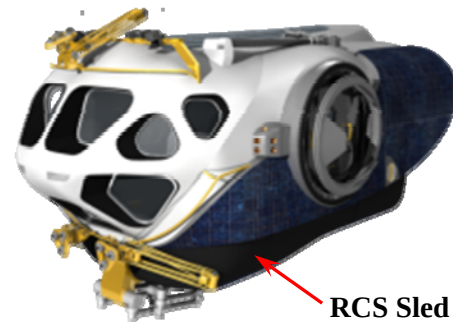
In the following discussion we focus on the MMSEV in a NEA mission scenario. This vehicle is unique in terms of its level of flexibility and its development heritage. This vehicle is a result of years of lunar rover field demonstrations. It evolved as a multipurpose vehicle with a high degree of configurability and modularity. This vehicle level modularity is now being extended to operations beyond cis-lunar space to Near Earth Asteroid.

MMSEV Surface Rover version



Mobility Chassis

MMSEV Near Earth Asteroid Version



RCS Sled

Figure 4.—Multi-mission space exploration vehicle variants: MMSEV provides the common platform with the flexibility to configure the vehicle for specific missions. The Rover Mobility Chassis is interchangeable with the Reaction Control System (RCS) sled.

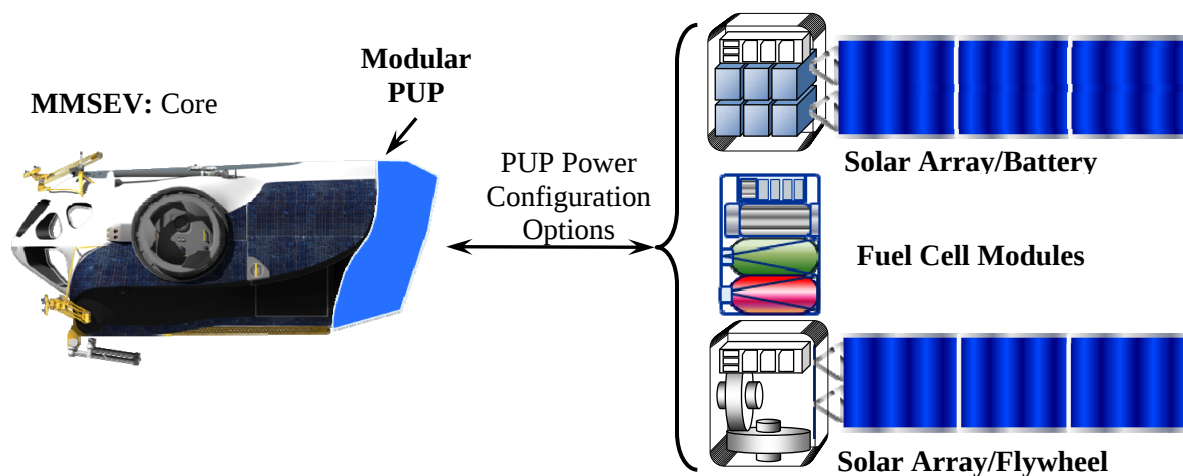


Figure 5.—MMSEV portable utility pallet power configurations. For specific missions, the PUP power subsystem may be configured by using interchangeable modular power building blocks.

As shown in Figure 4, for NEA applications, the MMSEV’s wheeled rover mobility chassis is replaced by a propulsive module that uses Reaction Control System (RCS) thrusters for mobility. A modular feature that is carried over from the rover concept is the PUP (illustrated in Fig. 5). The PUP is a detachable vehicle level module that configures the vehicle for a specific mission or sortie. The PUP is particularly important because it serves as a platform that can exploit the flexibility of modular power.

The Modular Power can provide combinations of Solar Arrays, Batteries and Fuel Cells that are appropriately scaled for the mission. Further, the modular PMAD features of AMPS Power will provide any power conversions required for adapting the power hardware to the vehicle. The integration of the hardware may be a “live” process where the hardware is internally powered and aware of the integration process. Power transmission may be suppressed until the AMPS system can validate connections and hardware readiness. To minimize crew operations the configuration of power hardware is handled via the plug and play network interoperability features. Data links to modules prior to connections may be provided by a wireless means such as Bluetooth or other protocols covered by IEEE 1451.

To assure a smooth and safe integration process embedded Supportability and Health Management features assess the status and readiness of individual elements before, during, and after they are integrated. Once verified that hardware is safe and properly configured, AMPS will enable power delivery.

A further benefit of the AMPS approach is that the PUP's power equipment need not be composed of dedicated hardware. The flexibility and supportability features also allow the hardware to be salvaged from other vehicles in the mission. For example a solar array may be “borrowed” from the CPS or SEP vehicles. The Solar Electric Propulsion stage, in particular, is capable of sparing a solar array to support MMSEV. Practical application of this approach is highly dependent on vehicle-to-vehicle commonality, rapid access to power hardware, the system scaling increment, and the ability of the donor vehicle to adapt to the reduced capacity temporarily or permanently.

NASA field demonstrations with the MMSEV and PUP can be used to validate the modular power approach. Demonstrations will be used evaluate the effectiveness of modular features and their impact on operational flexibility.

6.2 In-Flight Repair Scenario

This example scenario takes place on the Deep Space Habitat during a NEA mission. The DSH is a substantial vehicle that houses the crew for most of the mission. It has many design features that it inherited from the ISS habitable modules. In this case DSH also includes a logistics module that aside from providing mission consumables it provides spares storage and a modest work area.

Because all the vehicles in the mission stack have common systems the inventory serves as a common source for spares for all the mission vehicles, including spare power modules. To allow the flight hardware to be replaced by the limited dexterity of EVA encumbered astronauts or by remotely controlled robots, systems are accessed at the assembly level as ORUs. To avoid the mass penalty of sparing full sized ORU assemblies most spares are handled as subassembly and component level modules, as shown in Figure 6. Therefore, ORU units are retrieved and repairs are performed in the logistics module by replacing faulty sub assemblies or components. Once repaired, ORU is returned to service. If the subassembly is repaired by a replacement component then it becomes a spare subassembly.

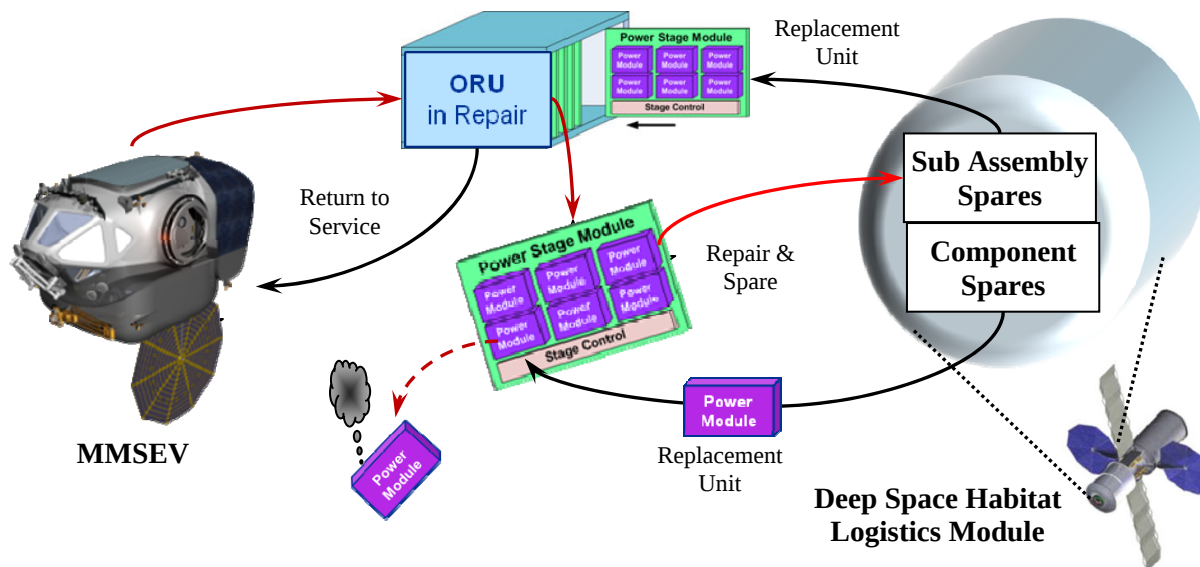


Figure 6.—In-flight modular repair scenario. A faulty Assembly Level ORU is removed and a faulty subassembly module is replaced allowing the ORU to be immediately returned to service. The subassembly fault is traced to a component module that is replaced and the repaired subassembly is placed in spares. In this scenario, modular assemblies and sub assemblies are preserved and only a component level module is consumed. The system is restored with minimum impact on logistics.

Examining the ISS logistics and maintenance practice reveals that repairs are not typically performed onboard the ISS below the ORU level (Ref. 4). Lower level repair on conventional electronic and electrical hardware implies a significant increase in tools, diagnostics equipment, process equipment such as soldering, coating removal and application equipment. Electronics repair studies indicate that there are substantial mass and volume penalties for this equipment (Ref. 7). Repair of non-modular component replacement requires substantial practiced skill and manual dexterity that is not typical of flight crews training. Grouping of loose components into “simple to replace” modules minimizes tools and process complexity.

A supportability study (Ref. 4) examined repairs of ORUs for space shuttle and space station at NASA depots and found that the actual removal and replacement of faulty hardware only made up 20 percent of the overall process. The remaining 80 percent involved problem diagnostics, hardware de-integration, post replacement re-integration and functional test and check outs. Much of the work was a consequence of the violation of system integrity that occurs during the repair process.

The AMPS approach is to modularize the lower level subassemblies and components in a manner that makes them easy to remove and replace with minimum disruption of integrity. Further diagnostics and built in functional tests will be embedded at these lower levels to quickly isolate the root cause and expedite the repair process. The Supportability and Health Management features also aid in reducing repair process complexity. HM monitors internal sensors and control loops. By tracking long term changes in a control feedback loop it can indicate that a particular component is degrading. Reporting this through the HM channels alerts the crew to a fault and identifies the specific replacement needed. This not only reduces diagnostics effort but also allows the crew to carry the specific spare to the site for an in-situ low level replacement. Supportability features can assist by rerouting power and isolating the unit for safe in-situ repair. Supportability Plug-and Play features also allow the module to be tested automatically before reconnecting to the system and automatically updating the system to indicate the presence of a new hardware. This type of modular repair operation scenario can be demonstrated and evaluated in concert with vehicle field demonstrations.

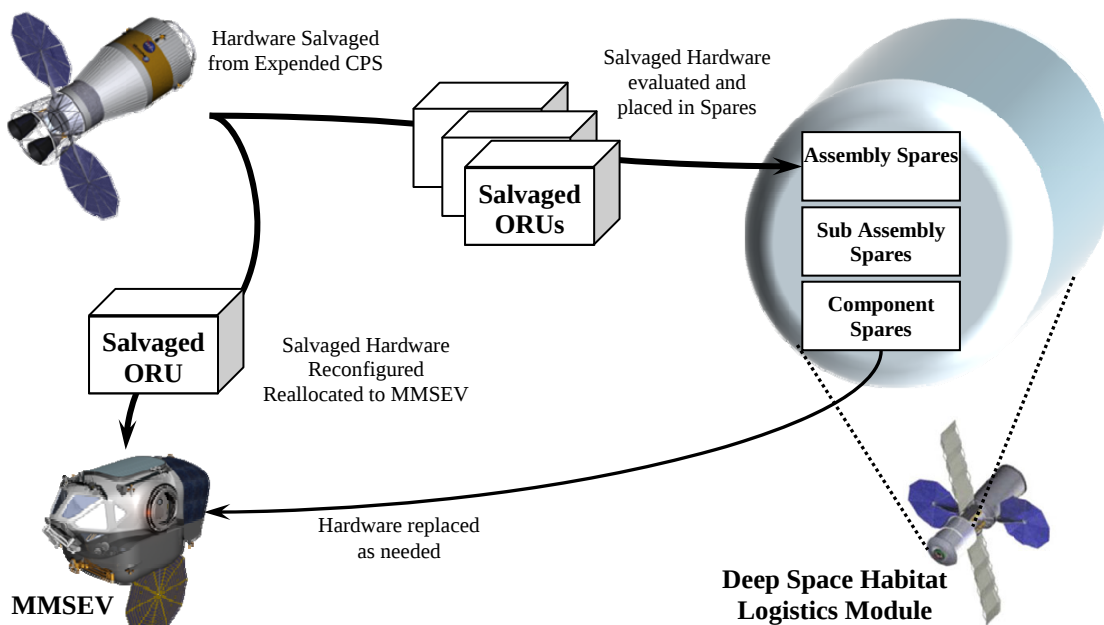


Figure 7.—Modular hardware salvage scenario. Salvaged hardware from expended vehicles may be reallocated directly to another vehicle or to DSH spares inventory. All salvaged hardware will need to be evaluated and reworked if needed before they are reused. Embedded Health management and supportability features will expedite this process. This approach also provides DSH with a source of assembly level hardware.

6.3 In-Flight Hardware Salvage Scenario

As noted earlier, modular power offers some opportunities to exploit other vehicles for system hardware. This can also apply to spares inventory. Even though spare sizes are minimized, DSH may still struggle to provide spares for all vehicles. In this scenario we consider another resource for flight hardware (Refs. 2 and 10) as illustrated in Figure 7.

Most vehicles are still functional after they have served their initial mission role and are thus a rich source of hardware. Commonality in power architectures, common interfaces, along with, mechanical and electrical encapsulation makes modular power hardware portable. Smart Plug and Play interfaces simplifies de-integration and re-integration process (Ref. 6). Using appropriate scaling increments assures that the modules are a manageable size for EVA and robotic handling.

There are a number of considerations for scavenging or salvaging hardware. Although hardware can be expected to be in good condition it may still experience degradation which will impact all the spacecraft in the stack. The crew will need to determine the relative condition of the power systems across all spacecraft. The crew will want to salvage the best for the remainder of the mission and that may mean removing hardware from the DSH or MPCV and replacing it with hardware from the other expended vehicles like CPS or SEP. This salvaging and redistribution operation ranges from small regulator modules to battery, solar array and fuel cell subsystems.

To sort out which units will be selected in a redistribution of hardware, the embedded supportability and health management features will, once again, assist the crew. Supportability and HM features can assess individual modules, report prior anomalies, indicate accumulated service life, and predict remaining life.

7.0 Modular Power Management and Distribution

7.1 The Approach to Modularity in PMAD Systems

Current practice in Power Management and Distribution design is to develop mission specific solutions. Each mission has unique loads requirements, power quality specifications, operational requirements, etc. As shown in Figure 8, PMAD elements (e.g., load and bus regulators, energy storage subsystem interfaces, and protection) are designed to optimally meet these unique system and subsystem requirements and cannot be used in any other vehicles. With future exploration dependent on multi-vehicle missions there is an opportunity to consolidate power system Design, Development, Test and Evaluation costs. To do this however, means that power systems need to share a common approach and architecture. These vehicles vary widely in their power needs; therefore, imposing a common power

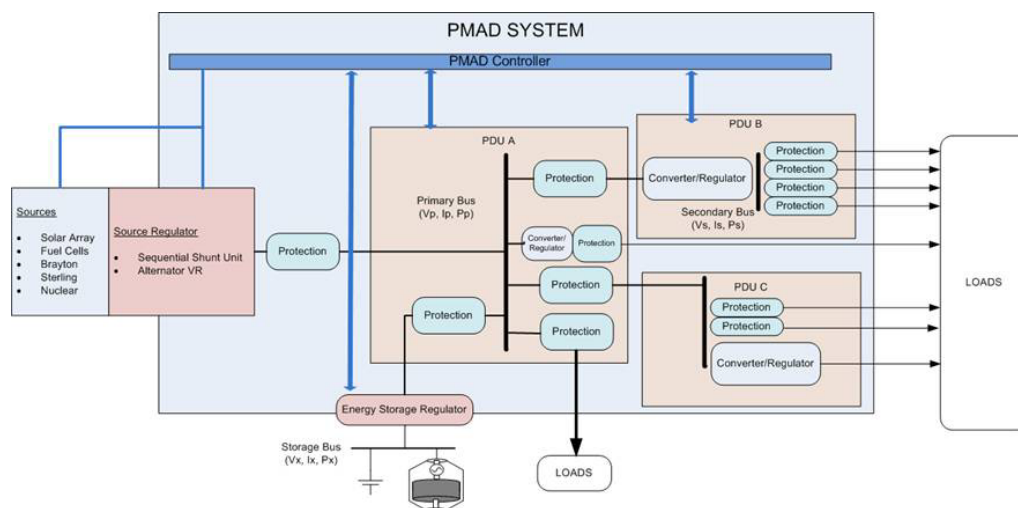


Figure 8.—Elements of a power management and distribution system.

quality specification is not sufficient to achieve true commonality. However, by organizing low level elements into modular building blocks, a power architecture that is scalable with substantial commonality can be built. PMAD system is composed of two types of electronic devices; power electronics and control electronics. The power electronics (includes electromechanical devices) conduct and direct the current and tend to scale in relation to the power loads. Control electronics manages the power electronics with low power mixed signal (digital and analog) devices that scale somewhat independently of power loads. A modular building block approach must account for differing scaling factors.

7.2 PMAD Module “Scaling Increment”

As discussed in Section 4.0, the scaling increment is the predefined module capacity associated with a building block. Several scaling increments may be needed to provide the flexibility to group elements in parallel and/or series combinations to meet the wide range of mission needs.

While different control techniques are required for different applications, regulation functions can all be addressed with common power converter designs. That is, solar array regulation, bus regulation, battery charge/discharge control, and load power regulation can all be done with common DC-DC converters (referred to as Flexible Power Modules). These need only be paralleled in sufficient numbers to meet the operational requirements.

A preliminary analysis of the HAT vehicle electrical systems requirements resulted in the identification of four modular converter ratings: 500 W, 750 W, 1 kW, and 2.5 kW that serve as the primary scaling increment for converters. With multiple increments in converter size one can mix and match the needs with minimum surplus capacity and the fewest number of parallel converters.

7.3 Modular Impact on System Redundancy

The secondary effect of the modular approach is to provide redundant paths for power delivery. On ISS, redundancy of PMAD systems is accomplished at the channel level, and requires that either the distribution system be re-configured (e.g., channel cross-ties closed) or low-criticality loads be shed. This approach is suitable for ISS with eight power channels and a total system capacity much larger than any individual load. These redundant channels provide a full power capacity with a substantial mass penalty which may not be acceptable for smaller spacecraft.

An advantage of the modular approach is the ability to continue operation but at a reduced capacity after a failure. The need for full continuous power depends on the phase of flight and the criticality of the system supported. For launch and landings, in particular, full power is essential. Other phases of flight could tolerate the degradation, particularly if it is a temporary condition and recoverable by a maintenance action by the crew. This is consistent with the desire to have “graceful degradation” where the crew has time to detect and respond to a failure.

By designing backplanes and associated controllers capable of accepting converters of multiple power ratings, inter-changeability results. This inter-changeability allows for the potential scavenging of power converters from a non-critical system to a higher criticality system.

An assumption made for the modular PMAD systems approach was that the converters would process all of the power in the same way that the baseline systems typically do. However, mass savings can be attained by using advanced topologies. The Series Connected Boost Regulator (SCBU), for example, is one such topology which implements a DC-DC analogously to an autotransformer. By using this connection the power converter need only boost a fraction of the total load power, resulting in significant mass savings (Ref. 11).

7.4 Modular Power Distribution Units

The regulators are paralleled to build-up an assembly level Power Distribution Unit (PDUs) to accommodate specific requirements. The following describes the modular elements used to define a Power Distribution Unit.

7.4.1 Control and Protection

System protection and switching functions can be accomplished with either solid-state or a hybrid combination of electro-mechanical and solid-state switchgear. These are packaged as Remote Power Controllers (RPCs), which consist of a family of solid-state switchgear of different ratings. RPCs also offer benefits such as active current-limiting, soft-starting, paralleling, etc. Modular RPCs are subassembly level modules connected to a chassis backplane. They are a mix of capabilities in terms of channel count and channel capacity. Based on the HAT vehicle analysis, RPC composition ranges from multi-channel 5 A modules to single channel 250 A modules.

7.4.2 Modular Chassis

For all functions, excluding battery controllers, four modular chassis were identified to accommodate the typical PMAD functions of regulation, switching, and protection. All chassis types accommodate RPC cards, housekeeping, communication, data acquisition cards and an application specific control card.

Chassis Types:

- Type 1 Chassis accommodates five 500 W converters and nine RPC cards.
- Type 2 Chassis accommodates five 2.5 kW and 9 RPC cards.
- Type 3 Chassis accommodates switchgear-only.
- Type 4 Chassis accommodates one 2.5 kW (or five 500 W) converter, and it has fewer slots for RPC cards.

Note: An advantage of the modular design approach is that a single 2.5 kW converter can be used in the Type 1 chassis if scavenging is necessary. Similarly, a single, or up to five, 500 W converters can be placed in any single 2.5 kW “slot” of the Type 2 chassis. It is possible to fit up to (25) 500 W converters in a Type 2 chassis.

7.4.3 Bidirectional Energy Storage Controllers

Modular batteries may incorporate bi-directional converters and controllers that are integrated with the battery chassis. Battery regulators have the additional requirement to provide bi-directional power flow which separates them from other regulators. Once again a unique power need is met by using an appropriate selection of scaling increments and using them as modular building blocks. For battery charge/discharge regulation the modular scaling increments were determined to be 750 and 1000 W.

7.5 Modular PMAD Tech Development and Demonstration

A goal of AMPS PMAD is to develop a Flexible Power Module (FPM), illustrated in Figure 9 which is one of the power converters to be used as building block for any type of electrical regulator in a PMAD system. The design of the FPM targets four typical space power applications: solar array regulators, bus voltage regulators, battery charge regulators/discharge regulators, and load converters. The modules will be interchangeable (plug-and-play) and automatically configure themselves for the application. These FPMs will communicate with each other to offer power sharing and phase staggering to reduce overall EMI. Individual modules will be enabled or disabled based on demand to increase overall system efficiency and compensate for failed modules.

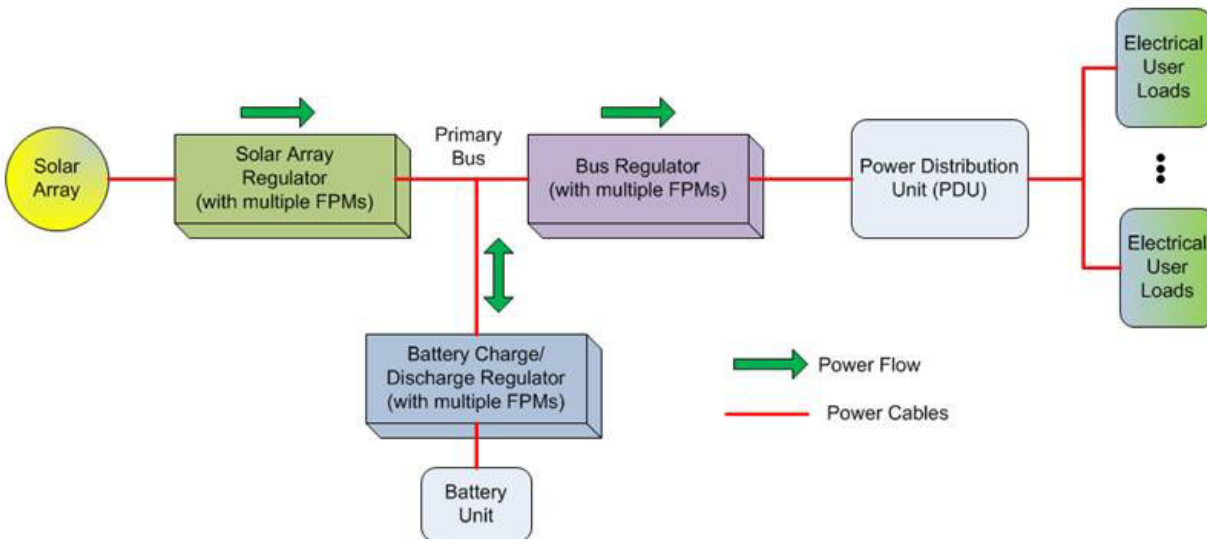


Figure 9.—Flexible power module. The FPM unit serves as a common interchangeable building block that is employed throughout the system for a variety of PMAD functions.

The FPM is being developed along three parallel paths. Path #1 uses COTS power converters to implement a solar array regulator to which custom controls are added to demonstrate a majority of the features of the FPM. Path #2 is a bus regulator using ISS power converters that allow for additional features to be demonstrated, such as phase staggering. Path #3 involves development of a bi-directional power stage to be used in all applications. Intelligent controls developed in the first two paths will be integrated with the power stage from the third path to demonstrate the flexibility and adaptability of the modular PMAD approach.

Currently, demonstrations of Path #1 and #2 have been successfully tested to prove basic functionality of these concepts. Path #1 was successfully tested in an end-to-end power system simulator, proving the power sharing, failure compensation, and increased efficiency concepts. Path #2 added pseudo-masterless control, serial communication, and phase staggering among the power converter modules. The bi-directional power stage of Path #3 is under development and will be combined with the controls proven in the first two demonstrations to yield the final prototype module. This module will be tested as a battery charge/discharge regulator, bus regulator, and solar array regulator.

8.0 Modular Solar Array Technology

8.1 Key Solar Cell Performance Parameters

The key parameters that characterize solar array performance are specific power (W/kg) and areal power (W/m^2). Various mission-related environmental effects and degradations affect both the solar array power and these parameters.

Another key performance characteristic is the acceleration capability. Normally, large solar arrays are designed for low accelerations because they are heavy and the added structure needed to maintain their integrity for higher accelerations add a prohibitive amount of mass. For the range of vehicles in this study, the option to fire thrusters after the solar arrays are deployed necessitates either stiffer solar arrays or retractable ones. The latter option is typically unacceptable due to risk involved in redeployment after performing a thruster maneuver (such as trans-lunar insertion). During the study, it was assumed that all vehicles had to endure 1 g acceleration except the MMSEV Surface Rover and Lunar Descent Module (which had a 2.7 g requirement) and the very large SEP vehicle (0.2 g requirement).

Voltage level was also a key attribute and 120 V was assumed for all vehicles except the SEP which assumed 300 V. These high voltages enable the reduction of electrical harness mass.

8.2 Solar Cell Technology Options

Two approaches were assumed for the solar cells. (1) Because of mass and size limitations, the SEP vehicle was assumed to use IMM (inverted metamorphic multi-junction) cells with an assumed beginning of life (BOL) efficiency of 34 percent. These cells are one tenth the thickness of traditional cells. These cells are assumed to be available in quantity for the large SEP vehicle for the medium to far term. (2) Thinned gallium arsenide triple junction solar cells with a BOL efficiency of 30 percent are assumed for use in the solar arrays of the remaining vehicles primarily because they will be available in large quantities in the near to medium term at lower cost than IMM cells.

8.3 Modular Solar Array Concepts

8.3.1 Folding Rigid Panels

A wing composed of multiple, modular panels could be utilized, although these are typically are used for low acceleration ($\ll 1$ g) and/or low required spacecraft power levels or when the structural mass needed to withstand accelerations can be accommodated. The following Figure 10(a) illustrates this type of solar array on ISS.

In the AMPS modularity study, due to the higher power levels and accelerations, folded rigid panels were not considered. The MMSEV Rover baseline was originally rigid panel solar arrays; however, a modular approach was able to replace the rigid panels with an adequately designed roll out solar array.

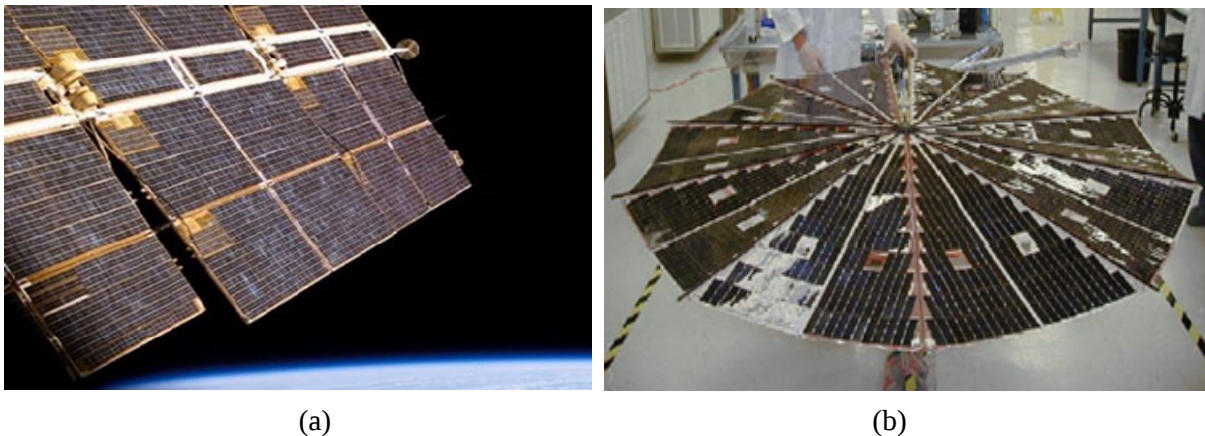


Figure 10.—Solar arrays examples. (a) Folding rigid panels used on ISS. (b) UltraFlex solar array wing deployed in ground tests. (NASA photo)

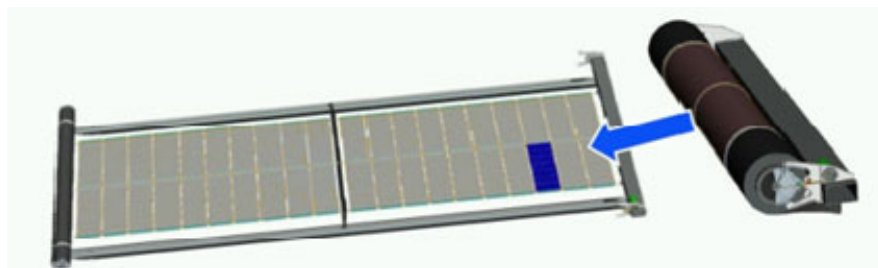


Figure 11.—A Roll Out Solar Array (ROSA) shown deployed on left and stowed on right (Ref. 19).

8.3.2 UltraFlex, MegaFlex

This type of solar array is best seen in examples such as Mars Phoenix (Ref. 12) and the CEV Orion (Refs. 13 to 15) spacecraft. Figure 10(b) shows an Ultraflex wing on the ground. Regardless of diameter (up to ~12 m or ~35 kW), the Ultraflex solar array (Ref. 16) is typically composed of 10 “gores” (i.e., triangular segments) to approximate a circle. Solar cells are attached throughout the gores into “strings” of series connected cells. Although these strings may potentially be able to be assembled modularly, this study assumed the gore was the minimum modular level. Larger Ultraflex wing designs (i.e., MegaFlex (ATK Corporation)) have been proposed for much higher power levels in one deployable structure (~30 m diameter, ~180 kW). The acceleration capability of the UltraFlex wings can be as high as 2.7 g (CEV Orion), although more likely 0.2 g for MegaFlex sized versions.

8.4 Solar Array Scaling Increments

Modularity based on solar arrays composed of numerous mass producible cell module building blocks was assumed. Cell modules are typically a series connection of solar cells (i.e., a string) to provide the voltage required by the power system. In this study, the cell module is rectangular and includes the cover-glasses for radiation shielding, coatings, substrate structure (if any), and mechanical/electrical interfaces. These cell modules are assembled into wings to obtain the required power levels with each vehicle’s wing sharing the maximum number of parts across the range of vehicles. Only ROSA-like wings shown in Figure 11 were considered due to the straightforward approach in modularizing at the string (cell module) level.

For ROSA-like wings, the strategy is to design the roll out tubes to have common diameters, but obtain more power by increasing the length (i.e., adding more solar cell modules). It was desirable to maintain the wing width (to maintain similar parts, increase commonality of structural analysis and testing). Comparing the required power levels and acceleration levels, it was determined that two kinds of ROSA-like wings were needed. The SEP vehicle wing width was 6.5 m but it requires two wing lengths (10.5 and 17.2 m), to accommodate electric propulsion plume impingement, with a 4 in. roll out tube diameter. For all the other vehicles, the width of the wing was 3.6 m with the wing lengths varying from 4.5 to 14.4 m and with an 8 in. roll out tube diameter. The reason the SEP roll out tube diameter is less than that of the other vehicle wings is because of the lower acceleration level (1/10 to 1/5 lower). The reason the range of wings can utilize the same 8 in. roll out tube diameter is because the vehicles with high acceleration requirements (2.7 g) have lower power levels than the ones with 1.0 g acceleration requirements (i.e., since power level is tied to the length of the wing, then a lower power level means the wing length, mass, and moment arm is lower, increasing its stiffness using the same diameter tube).

The cell modules are similarly uniquely designed between vehicles, namely the high voltage (300 V), IMM solar cells of the SEP vehicle have their own cell module design (0.77 by 0.23 m in size and 0.29 kg in mass), while all the other vehicles at the lower voltage (120 V) using thinned triple junction cells have their own common cell module design (0.77 by 0.23 m and 0.22 kg). Cell modules for all the 120 V vehicles are designed to handle the worse case common environments to minimize the unique designs and enable maximum modularity and economies of scale and common testing/qualification.

8.5 Modular Solar Array Logistics Benefits

Standardizing the number of ROSA module widths with their associated roll out tubes (diameter, material, and thickness) has the potential of reducing development and testing costs for the wing structures. Selection of optimal cell module sizes enables automated testing and inspection of modules. Modules that fail can be swapped out with ease. The SEP vehicle due to its size and number of wings (16) can be considered modular on that standpoint alone. SEP as part of a multi-vehicle mission, can serve as a source for spares for other vehicles. Once SEP’s mission phase is complete, the SEP arrays are suitable for salvage and reuse. The multiple deployment capability of the ROSA array simplifies the salvage process and its compact roll-up form is suitable for stowing and redeployment.

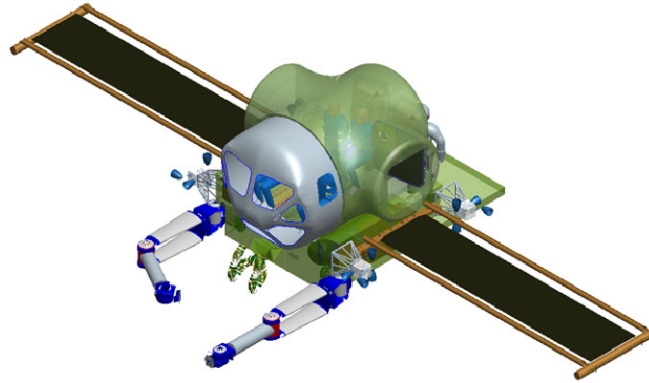


Figure 12.—ROSA array deployment demonstration. MMSEV and ROSA are shown integrated on to the RCS Sled to demonstrate array deployment and its behavior during RCS propelled maneuvers. (Credit: Rafael Jimenez NASA JSC).

8.6 Modular Solar Array Development and Demonstration

In 2012 AMPS worked in concert with the MMSEV project at NASA Johnson Space Center (JSC) to demonstrate the multiple deployment capabilities of the DSS ROSA array. Figure 12, shows a three-dimensional (3D) model of ROSA demonstrator integrated with a MMSEV vehicle mockup in its near Earth asteroid configuration. MMSEV and ROSA are supported on the Reaction Control System (RCS) Sled. The RCS Sled is an air bearing suspension system that enables the vehicle to maneuver using cold gas jets, in simulated low gravity operations.

9.0 Modular Battery Technology

The battery is an ideal example of a system composed of simple modular blocks. Battery capabilities are defined by the characteristics of the fundamental cell unit. The selection of the cell chemistry and geometry translate into battery characteristics and performance.

9.1 Performance Parameters

Major battery design drivers include the Amp-hour (Ah) capacity, peak and average currents, and voltage that the battery is required to deliver, as well as the cycle life, operational life, and redundancy requirements on the battery. Ah capacity, current, and voltage define the size of the battery. Fixed cell size establishes the Ah, current capacities and voltage increments. Ah capacity and the current scale up with the number of cells in parallel. Voltage scales by the number of cells in series. Life requirements define the extra margin required to be able to perform the required functions at the end of life (Ref. 20). Redundancy requirements determine the number of extra strings or batteries required to meet reliability, loss-of-crew, or loss-of-mission requirements. Overall, the primary attribute used to choose between design options for a given set of requirements is usually mass.

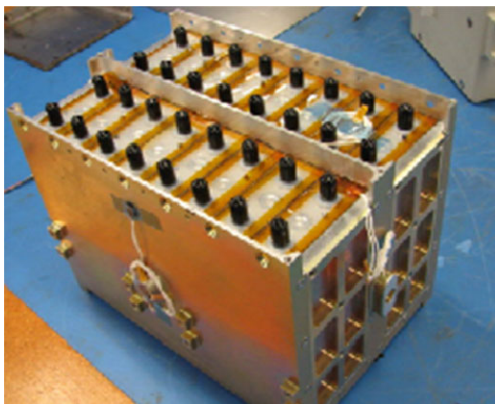
9.2 Battery Chemistry and Geometry Options

Current spacecraft batteries are mainly designed using lithium-ion battery technology for any mission that requires recharging. Other rechargeable battery chemistries are available, but their energy per unit mass is not as high at the current time. Lithium-ion technology has a variety of choices available in “space-qualified” cell designs. Lithium-ion cells are available in prismatic, cylindrical, and pouch formats. Pouch and prismatic cells require compression to achieve their optimum performance, while cylindrical cells do not. Pouch cells also have more specific handling requirements to avoid damage to the internal components. As shown in Figure 13(b), cylindrical cells are stable pressure vessels and suited for space with little additional structure.

9.3 Modular Battery Concept

Lithium-ion cells are available commercially in a large range of Ah capacities. The Ah capacity and current requirement of the battery can be met by using a large number of small Ah capacity cells or by using a small number of large Ah capacity cells. For safety reasons, overheating of any cell in a lithium-ion battery should be avoided. Overheating can be caused by overcharging, short circuit, cell reversal, or over-temperature of any cell. These conditions are normally avoided by controlling the charge/discharge of the individual cells and/or extremely close matching of the cells in the battery to ensure similar performance during operation. Matching and control of fewer numbers of large capacity cells is easier than that of large numbers of smaller capacity cells.

AMPS modular batteries will be closely coupled with charge/discharge functions provided by PMAD. Modular batteries will also incorporate Health Management largely through extensions of the charge/discharge controls. Not only will HM monitor battery health it will keep the system apprised of cell level changes and in some instances provide the capability to isolate a faulty cell while keeping the remaining cells safe and in operations. PMAD control can use power converters to bridge the lost cell and boost output voltage making the fault transparent to the user.



(a) Prismatic Cells



(b) Cylindrical Cells

Figure 13.—Common prismatic and cylindrical cell geometry. (a) Prismatic cells tend to pack more efficiently in terms of volume but need additional structure to constrain the internal pressure in high vacuum space applications. [NASA Photo] (b) Cylindrical cell geometry provides a suitable pressure vessel with minimum additional packaging. [Photo Permission: Saft Specialty Batteries] (Ref. 24).

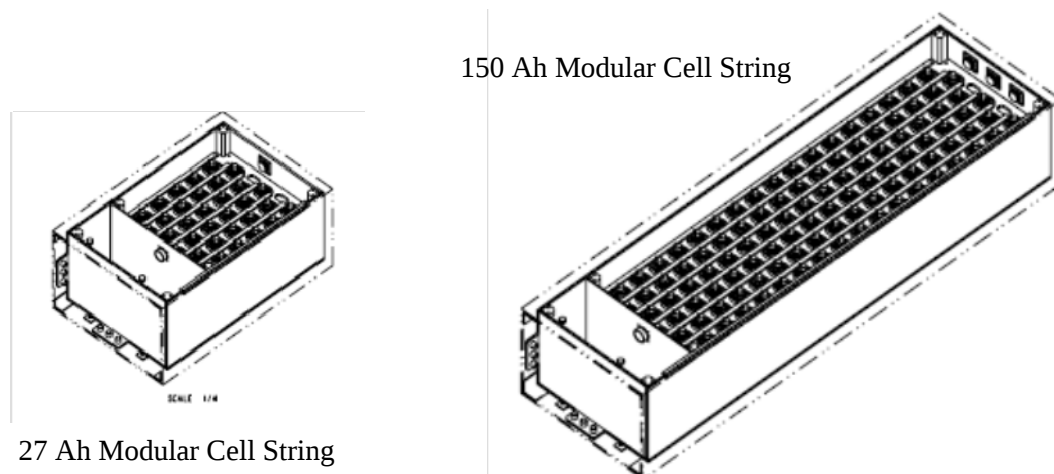


Figure 14.—Conceptual drawings of 27 and 150 Ah. Two modular concepts at scaling increments of 27 and 150 Ah were defined and used in cost modeling. [Credit: Kathleen Sukel, Vantage Partners, LLC].

9.4 Battery Scaling Increment

The battery beginning-of-life Ah capacity requirements (including redundancy and the extra margin required to meet end-of-life requirements) of various missions considered by the AMPS program sorted into two major types. Several missions had Ah requirements ranging from 23 to 76 Ah; others had Ah requirements ranging from 126 to 614 Ah. Peak discharge current requirements ranged from C/32 to 1.26 C. All missions had a requirement to support a 120 V bus. This range of requirements was met by designing two module types using lithium-ion cells designed to handle the appropriate current: a 27 Ah module and a 150 Ah module, both of which operate at approximately 120 V shown in Figure 14. These two sizes of modules could be used in integral numbers to meet the requirements of all of the missions under consideration. Three types of cells available from current battery suppliers were considered in conceptual designs: larger capacity cylindrical cells produced by SAFT, prismatic cells produced by Yardney, and commercially available small capacity cylindrical 18650 cells (Ref. 21). After comparison of the mass and the complexity of control of the designs, larger capacity cylindrical cells were chosen for the conceptual design. The 27 Ah module uses 33 SAFT VES 100 cells in series (Ref. 22). The 150 Ah module consists of 33 “virtual cells” in series, where the “virtual cell” consists of 3 SAFT VES 180 cells in parallel (Ref. 23).

9.5 Modular Battery Logistics Benefits

A common modular battery also reduces recurring logistics cost. If every spacecraft in a given mission uses the same types of modular battery then they could share a common source of flight spares. This reduces the overall spares inventory and improves supportability. Modular batteries would be primary targets for hardware salvaging operations. For example, modular batteries could be salvaged from an expended CPS or SEP vehicle and reused as spares or reallocated to another system.

10.0 Modular Fuel Cell Technology

10.1 Key Fuel Cell Performance Parameters

The factors that drive the design of a fuel cell power plant are primarily mission driven. The peak and nominal power required defines the size of the fuel cell stack and balance of plant. This requirement defines not only the number of cells and/or stacks to be included, but also the size of the cells or stacks.

Typically, a power-plant is characterized by the specific power (W/kg) and power density (W/l) of the power-plant as a whole. The voltage to be delivered to the vehicle bus by the fuel cell power-plant also impacts the design of the fuel cell stack. Higher voltages require a larger number of cells and/or stacks and how those cells or stacks will be arranged, i.e., series/parallel arrangements.

Total system energy, in Watt-hours (Wh), is driven by mission power level and mission duration. In long duration missions, the system mass is dominated by the mass of the reactants and storage tanks. The fuel cell hardware may represent a relatively small fraction of the mass.

Specific power (kW/kg), system efficiency, power density, desired peak to nominal power delivery ratio are typical parameters imposed by the mission. Fuel cells, however, impose their own requirements on the vehicle including, reactant pressure and flow rate, reactant purity, and heat loads handled by the vehicle thermal system. Future missions beyond Earth orbit will have additional requirements such as fuel flexibility.

The flexibility of a fuel cell technology depends on its ability to utilize available reactants. This includes reactants scavenged from propulsion systems or reactants extracted from in-situ sources. Where some designs require pure hydrogen/oxygen, others provide flexibility to operate on relatively impure reactants or hydrocarbon fuels.

Reliability and redundancy requirements also affect the design of the power-plant as a whole. Higher required reliability not only impacts how many redundant components are included within the power-plant design but also how those redundant components are handled, i.e., actively operating at all times within the power-plant or unpowered but available on a stand-by basis to take over a key function within the power-plant.

Vehicles and their Design Reference Mission requirements influenced the selection of fuel cell technology for the Modular Fuel Cell. The HAT study vehicles were predominately solar array + battery architectures and did not include fuel cells. The AMPS project determined that this approach did not account for opportunities to exploit in-situ resources found at surface destinations such as the Moon and Mars. Therefore, the Lunar Lander Earth Orbit Rendezvous and the MMSEV Rover were deemed as likely users of Modular Fuel Cell technology. This narrows the mission set and elevates the importance of flexibility, in terms of, reactant types and reactant sources.

10.2 Basic Fuel Cell Concepts

Fuel Cells are electrochemical devices, similar to batteries, which convert chemical energy to electricity. They use a fuel, such as hydrogen and oxygen to produce electrical power. The fuel cell reaction also creates water and heat as by-products.

The electrochemical reaction that produces power takes place within the cell stack but all the supporting processes are provided by the remaining “balance of plant” (BOP). The balance of plant is responsible for any preconditioning of reactants, moving reactants into the stack, removing by-products (water) and removing waste heat. The balance of plant interfaces with the vehicle to access stored reactants, transfer waste heat, vent reactants, and move product water out of the power-plant to be used by the crew, vented overboard, or reused in a closed loop regenerative system.

Like batteries, fuel cells can be primary (non-rechargeable) or regenerative (rechargeable). Primary fuel cells, as can be seen in Figure 15, are composed of a fuel cell stack which produces the electrical power and a balance of plant which delivers the reactants to the fuel cell stack and removes the product water and waste heat.

The voltage and current produced by a fuel cell is determined by the design’s cell stack series and/or parallel arrangement and the size of the individual cells. Unlike batteries, the fuel cell will continue to provide power as long as fuel and oxidant continue to be fed into the fuel cell stack. Unlike solar arrays, the compact and rugged fuel cells are suitable for underwater vehicles, aircraft, and automotive applications.

Solar arrays and fuel cells are often seen as alternative power sources. Solar is seen as renewable while fuel cells are limited by reactant supplies. A hybrid system composed of both fuel cells and solar arrays can exploit the benefits of both. In a Regenerative fuel cell system, as shown in Figure 16, the reactants and water are part of a closed loop system where the water is reconverted back to reactants by a solar powered electrolyzer. This is similar to rechargeable batteries except that the regeneration can occur concurrently while the fuel cell continues to produce power without diminishing as long as reactant production stays ahead of consumption.

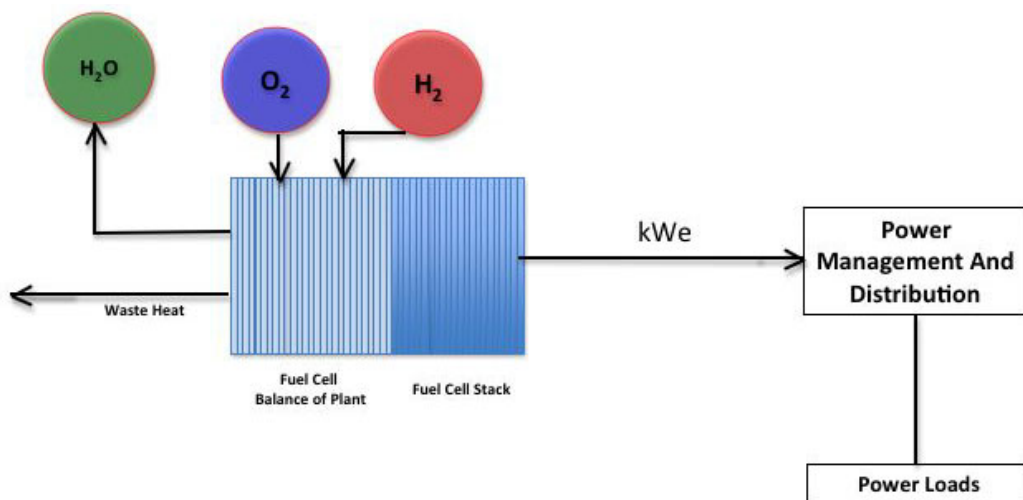


Figure 15.—Primary fuel cell block diagram.

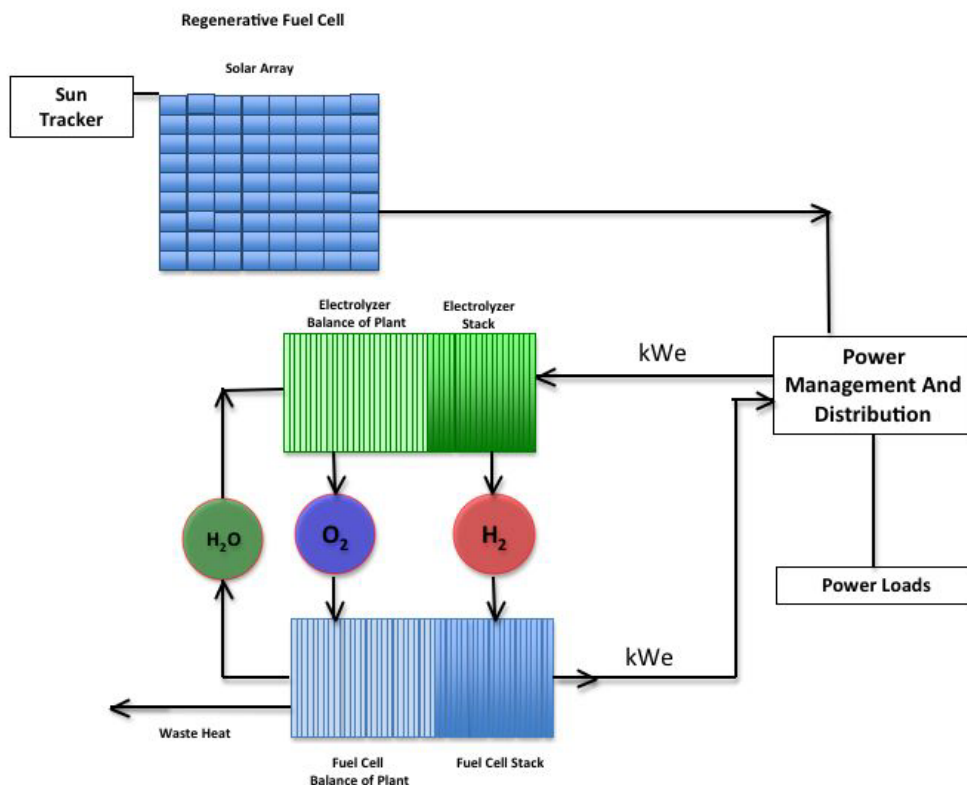


Figure 16.—Regenerative fuel cell system block diagram.

10.3 Fuel Cell Chemistry and Balance of Plant Options

Only three types of fuel cell chemistries have actively been investigated for space applications, specifically, Alkaline, Proton Exchange Membrane (PEM) and Solid Oxide Fuel Cells (SOFC). Alkaline fuel cells have been the workhorse power source from Apollo to Shuttle Orbiter. Concerns with usable life, cost and sensitivity to contaminants, have driven the investigation into other options.

PEM fuel cells operate at relatively low temperatures (80 °C) and can bootstrap themselves to operational status as needed. PEM fuel cells typically operate using hydrogen as a fuel (although they have been shown to operate on methanol/air) and are generally intolerant of most reactant impurities. Three basic types of supporting Balance of Plant (BOP) designs have been under investigation for PEM fuel cell systems, active, passive and non-flow thru.

SOFC operate at higher temperatures (>600 °C) and need to be pre-heated to that temperature before the fuel cell reaction can begin. Like PEM and alkaline fuel cells SOFC's can operate directly on hydrogen and air or oxygen, but also operate with impure hydrogen (as would be expected from ISRU operations), or reformat from hydrocarbon fuels and methane. SOFC's are also very tolerant of most impurities while the waste heat from SOFC's is high enough to support cogeneration (via Stirling, turbines, etc.) for additional power and potentially increasing the overall system efficiency to greater than 70 percent.

10.4 Modular Fuel Cell Concept and Scaling Increment

Fuel cell power-plants have traditionally been designed incorporating one fuel cell stack with one balance of plant. The BOP delivers preconditioned reactants to the stack, removes water and waste heat. The BOP provides the interfaces with the vehicle reactant stores, thermal control, vent lines, and external water processing. The total power-plant is normally scaled to meet the entire power requirement of the vehicle. System redundancy is provided by additional fuel cell power-plants operating in parallel as shown in Figure 17(a) to (c).

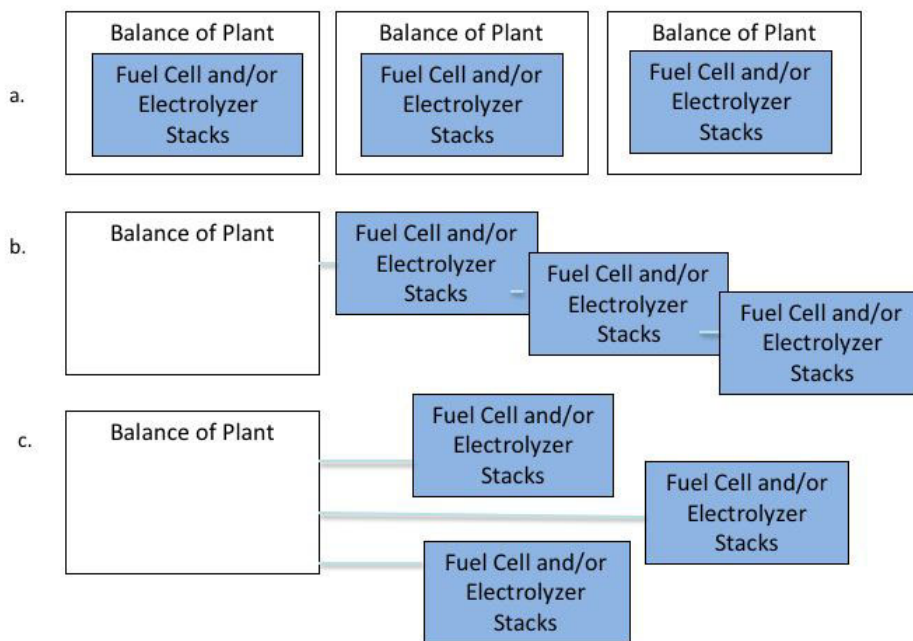


Figure 17.—Potential approaches to fuel cell system architecture.

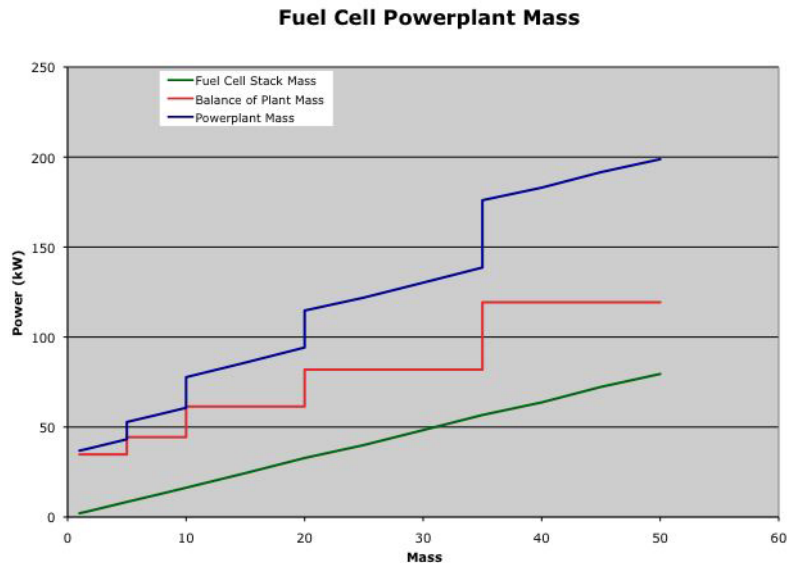


Figure 18.—Fuel cell stack and balance of plant mass with increasing power.

Sized to meet the application power requirements the fuel cell stack scales linearly by adding cells and/or rescaling the basic cell size. An alternative method is to expand the power-plant by adding additional stacks. The power-plant has a variable output and thus, BOP fluid lines and control components are sized to cover a range of flow rates.

Components are sized for maximum flow with margin. Beyond that the lines and controls jump to the next commercially available size step. As a result the BOP would follow a continuous increase in power with a stepwise increase in component size as shown in Figure 18. Therefore a given balance of plant design can typically accommodate a range of power levels about some nominal value before stepping up to the next size increment.

The proposed modular fuel cell handles redundancy for the BOP and the modular cell stack with distinctly different approaches. Further, the sizing of the BOP and the modular cell stack differ. At first look, it may seem advantageous to size one power-plant for the largest vehicle power demand needed, however this may levy a large mass penalty upon the vehicle. For example, a balance of plant sized to deliver sufficient reactants with matched thermal rejection to handle 12 kW may be sufficient to handle the potential growth of vehicle power requirements. For higher power requirements, instead of adding more 12 kW Fuel Cell subsystem, a BOP with extra capacity can be built and separate modular fuel cell stacks added. For this same example, the attached modular fuel cell stacks are arranged as three 4 kW units to handle the anticipated power requirements. Additional 4 kW units can be added incrementally.

For redundancy considerations, the three primary 4 kW stacks operate in parallel and each supports 33 percent of the 12 kW total output. If one unit fails the remaining two units can be ramped up from 33 percent total load to 50 percent of total load each. This is an increase of roughly 1.5 times and well within a fuel cell stacks range. The power thermal control interface will need to provide the additional heat rejection margin.

However, if two of the three fail the remaining single stack would need to boost output by 3 times to carry the full load. This is much more difficult because there would be an attending decrease in efficiency and increase in waste heat. It is more reasonable to push the single stack output up between 1.5 to 2 times nominal and let the overall vehicle power drop to a level between 50 to 66 percent.

This could be a temporary situation that can be handled by a so called Hot (Standby) Spare. This would be a 4th unit that sits in a standby condition and is started by the BOP rerouting fluids from the faulty unit to the hot spare unit. This assures that even after 2 faults the system still provides full capacity without overstressing the hardware. The hot spare unit is another 33 percent more mass plus the additional isolation valves, fluid lines, and controls.

Alternatively, a modular cell stack “cold spare” approach can be used if the vehicle can tolerate the reduced capacity temporarily. In this case, spare module can be salvaged from another vehicle that has been expended but still contains functioning fuel cell hardware. This alternative eliminates the mass penalty of a hot spare cell stack.

10.5 Modular Fuel Cell Technology Development and Demonstration

A spacecraft fuel cell is literally an electrochemical power plant that often runs on the fuel/oxidizer reactants that it taps from the propulsion system. Their innate complexity makes them a challenge to integrate into a modular package. Modularization of a fuel cell power-plant begins with packaging the modular components to simplify the interfaces. In the case of the Non-Flow-Through (NFT) Fuel Cell technology, the process of separating the water from the oxygen is done within the fuel cell stack rather than within the balance of plant, potentially simplifying the interface between stack and balance of plant.

NASA Glenn Research Center has been working with Infinity Fuel Cell and Hydrogen, Inc. to develop non-flow-through (NFT) proton-exchange-membrane (PEM) fuel cell power systems. The goal of the AMPS fuel cell demonstrations so far has to evaluate the technology for robotic and human rover vehicles.

10.5.1 NFT Fuel Cells SCARAB Demo

In the first Fuel Cell demonstration within the AMPS program, the NFT fuel cell technology was being integrated onto surface system demonstration vehicles as shown in Figure 19. A 16-cell, 132 W developmental NFT fuel cell power-plant was used to augment the power delivered to the Carnegie Mellon University’s SCARAB rover (Ref. 25). This modest developmental test was intended to demonstrate a NFT fuel cell system on a test vehicle as a precursor to larger demonstrations. The successful tests performed in late 2011 helped to identify integration issues and evaluate features that in turn can improve the NFT Fuel design for future vehicle operations.

10.5.2 3-kW NFT Fuel Cells MMSEV Demonstration

The goal of the NFT Fuel Cell technology development is to develop and produce units of progressively higher capability. The next steps are 1 and 3 kW units. The 1 kW NFT unit is currently undergoing laboratory evaluation testing. The new design integrates parts of the fuel cell “balance of plant” hardware onto the stack interface plates, as can be seen in the power-plant mockup in Figure 20. A 3 kW NFT Fuel Cell unit is being developed that is expected to match the power the core MMSEV vehicle loads, (currently, estimated at approximately 3 kW). A demonstration of this unit onboard the MMSEV prototype is planned in FY 13. The 3 kW NFT Fuel Cell developed by Infinity Fuel Cell and Hydrogen, Inc. is composed of 144 cells with a nominal stack voltage of 120 Vdc to produce a nominal stack power level of 3 kW and a peak level of 6 kW.

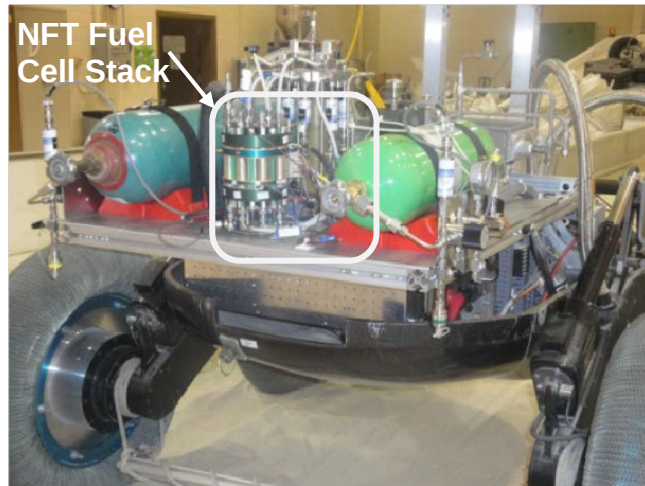


Figure 19.—Carnegie-Mellon University's SCARAB Rover with NFT fuel cell technology installed. [NASA Photo].



Figure 20.—3 kW non-flow through fuel cell power-plant mock-up. This mockup unit illustrates the integration of the balance of plant onto the fuel cell stack itself. This approach could enable a more compact PEM fuel cell power-plants. [NASA Photo].

11.0 Health Management and Supportability Technology

The effectiveness of a Modular Power System depends on the successful development and application of Health Management and Supportability technologies. Normally, crew and ground operations, logistics, and specialized equipment are required to maintain a system and assure a high degree of system availability. Health Management and Supportability are tightly coupled to provide embedded solution to system health and maintenance.

11.1 Supportability Dependency on Health Management

The long term operational support of space flight systems has become an important program cost issue in an era of long lived space facilities such as the ISS (Ref. 4). Until recently, ISS had the benefit of a robust logistics infrastructure provided by the Space Shuttle. The Space Shuttle allowed the program to move Orbital Replacement Units between ISS and ground based depot on a regular basis. The ORUs were replaced by the crew manually or by robotic means and the detailed “root cause” diagnostic and repairs were off loaded to the depots. Note that without isolating a problem’s root cause, we cannot improve the hardware reliability.

Without the benefits of a logistics infrastructure, long missions beyond low Earth orbit have a much greater need to carry spares and related repair and test equipment to perform repairs in-situ. This collides with the extremely scarce upmass capacity.

As discussed in Section 4.0 there is substantial mass savings achieved by sparing at levels below the complete ORU (Ref. 8). There is, however, a greater dependency on external repair, diagnostic and test equipment particularly, when searching for the root cause of a problem. Not only is there an uncertain mass impact, but there can be a substantial growth in the amount of crew time dedicated to maintenance. Based on the Lunar Surface Systems Supportability Study (Ref. 4) the time required to perform a repair grows 5 to 10 fold depending on the level of replacement. As noted in Section 6.0, roughly 80 percent of the repair process time involves diagnostic, integration and post repair functional tests. Proper modular encapsulation that simplifies interfaces to minimize violation will be a major step toward supportability. However, this must be matched with greater insight into root causes with embedded diagnostic and prognostic capabilities.

A negative consequence of integrating functions into modular blocks is the tendency to physically hide details of the internal functions. This makes it very difficult to diagnose the root cause of problems. Measurement ports and test points are added but they increase complexity and the number of intrusive interfaces. There is thus greater demand for a built in test (BIT) to evaluate system functions. Simple functional BIT tests, however, do not indicate the root cause of a problem they only indicate what is not working. Embedded health management and supportability becomes enabling technologies for increasing system supportability while minimizing external equipment and operational complexity.

Embedded Health Management (HM) exploits sensors and measurements that are already in the system usually as part of internal control loops. HM typically looks for slowly progressive changes in control loop signals that indicate the onset of a fault. This early warning allows the crew to prepare for, and where possible, preempt the fault with corrective actions. This may include changing operations to minimize degradation or switching hardware to channels with lighter loads. The early warning also lets the crew investigate behaviors that further identify the root cause. Further HM will monitor and analyze sensor signals for inconsistencies between with related sensors to determine if sensor rather than the hardware is faulty.

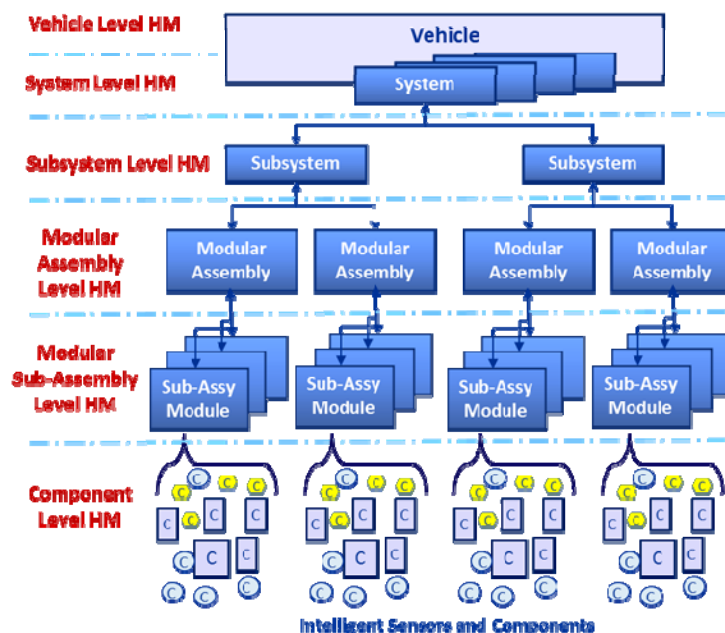


Figure 21.—AMPS health management. Health management spans the range of hardware from vehicle level down to component level.

These features also apply to scenarios where hardware is salvaged and reallocated. They are useful in assessing the health of the salvaged unit and the remaining operational life. These features can dramatically improve the effectiveness of modular power as a supportable system.

11.2 Health Management and Supportability Performance Parameters

Health Management and Supportability will be evaluated by its ability to:

- Detect the onset of a fault sufficiently in advanced to allow the crew to preempt the fault.
- Predict the time remaining before failure
- Pinpoint the fault to individual components.
- Determine the root cause in sufficient detail to prevent a recurrence.
- Identify, disqualify and compensate for faulty sensors.
- Assess the remaining life of any element
- Embed an “electronic log book” to store unique information such as, module ID, current configuration, operating hours, estimated remaining life

11.3 Health Management and Supportability Concept

In order for a modular power system to deliver maximum benefit, health management functions will need to be integrated with the overall system control functions in the form of a hierarchical and distributed architecture shown in Figure 21. Many health management functions can be delegated to lower levels of assembly closer to the potential fault sources. This architecture makes use of intelligent sensors and components with embedded processing capability that makes it possible for health management to function at lower levels and subsequently reported up the hierarchy. In addition, distributed and hierarchical monitoring, diagnostic and prognostic approaches will allow the intelligent sensors and components to incorporate local knowledge and history to enable local health assessment.

The locally assessed health knowledge then drives higher-level health management models that incorporate high-level knowledge (e.g., analytical and/or empirical models) that allows the integration of lower-level knowledge through interdependency relationships and allow consistency checks of lower-level data. As an example, intelligent sensors can actively determine their own condition and provide an indication of the quality of the sensed data that they are providing. This additional health assessment information can then be included in the evaluation and decision-making by higher functions in the hierarchy. Another benefit of distributed intelligent components is the potential for collaborative processing of complex algorithms in parallel. Modular and distributed HM enables increased flexibility, portability and reusability of the modular components.

11.4 Health Management Development Framework

The distributed architecture for health management and system level-control will be achieved through the development of a software framework that enables the flexible organization and structuring of all required health management, supportability and control functions. This framework will provide a scheme for encapsulation of the knowledge, behavior and interactions associated with the system. The framework is intended to enable developers to create health management and supportability software objects that will run on systems composed of distributed heterogeneous processors (e.g., embedded processors, microcontrollers, smart sensors and smart components). It will accommodate a range of processing capabilities including processors that need, so called, “light-weight” implementations due to computational limitations. In addition, the framework will allow for the definition of standard interfaces enabling communication of inter-process data and commands between distributed elements. To assure interoperability, the framework will be based on open system industry standards for data interchange.

To minimize growth in complexity, the framework will emphasize code re-usability at all levels of the architecture. It provides the flexibility to implement and execute health management, control and supportability functions throughout the hierarchy from vehicle system-level control, decision-making and fault management all the way down to low-level monitoring, diagnostic, prognostic and remediation response processes. Plug-in libraries enable the user to select and use a wide variety of control, decision-making, and HM algorithms, various system models, built in test (BIT), and self-contained analysis routines.

The framework will accommodate advanced diagnostic and prognostic algorithms based on analytical system models, empirical data acquired from hardware characterization tests, or hybrid combination of analytical and empirical techniques. Additionally, the framework will accommodate advanced control algorithms such as “agent-based” controls and power/load flow optimization. Verification of the distributed architecture that results from this framework will be accomplished through implementation and demonstration on the AMPS project’s PMAD development breadboards.

12.0 Conclusion

For the Advanced Exploration Systems (AES) Modular Power Systems (AMPS) project at GRC the goal is to develop a modular power architecture composed of technologies for power generation, energy storage, power distribution and health management that will reduce the cost of future space systems. Examining the several new vehicles required for future missions, there is a clear opportunity to consolidate the power system development into common power architecture and reduce development cost. In addition, the vehicle recurring and life cycle cost is reduced because the common set of spares, common equipment and common procedures reduces integration complexity and logistics. Modular power is believed to enable spacecraft to be reusable, serve multiple missions, and contribute hardware to a growing space infrastructure.

Commonality is necessary but not sufficient for defining modular power systems. To assure flexibility and scalability a modular approach must incorporate standardized smart interfaces that provide interoperability that allow the modules to be reused and reconfigured to meet changing needs. To manage this flexibility and keep hardware organized, each module will need embedded supportability and health management features that preserve the module identity, their current configuration, operating history, and cumulative operating life. Supportability and Health Management will assist the crew in predicting faults, diagnosing and isolating problems, and quickly restoring full capability with minimum complexity.

In the next few years modular power system technologies along with health management and supportability technologies will continue to evolve. Demonstrations are expected to provide validation of the AMPS modular power concept as an essential element in the development of multi-mission exploration vehicles.

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1. REPORT DATE (DD-MM-YYYY) 01-06-2013		2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Advanced Modular Power Approach to Affordable, Supportable Space Systems				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Oeftering, Richard, C.; Kimmach, Greg, L.; Fincannon, James; Mckissock, Barbara, I.; Loyselle, Patricia, L.; Wong, Edmond				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER WBS 756414.02.02	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191				8. PERFORMING ORGANIZATION REPORT NUMBER E-18549	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001				10. SPONSORING/MONITOR'S ACRONYM(S) NASA	
				11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2013-217813	
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Categories: 12 and 20 Available electronically at http://www.sti.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 443-757-5802					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Recent studies of missions to the Moon, Mars and Near Earth Asteroids (NEA) indicate that these missions often involve several distinct separately launched vehicles that must ultimately be integrated together in-flight and operate as one unit. Therefore, it is important to see these vehicles as elements of a larger segmented spacecraft rather than separate spacecraft flying in formation. The evolution of large multi-vehicle exploration architecture creates the need (and opportunity) to establish a global power architecture that is common across all vehicles. The Advanced Exploration Systems (AES) Modular Power System (AMPS) project managed by NASA Glenn Research Center (GRC) is aimed at establishing the modular power system architecture that will enable power systems to be built from a common set of modular building blocks. The project is developing, demonstrating and evaluating key modular power technologies that are expected to minimize non-recurring development costs, reduce recurring integration costs, as well as, mission operational and support costs. Further, modular power is expected to enhance mission flexibility, vehicle reliability, scalability and overall mission supportability. The AMPS project not only supports multi-vehicle architectures but should enable multi-mission capability as well. The AMPS technology development involves near term demonstrations involving developmental prototype vehicles and field demonstrations. These operational demonstrations not only serve as a means of evaluating modular technology but also provide feedback to developers that assure that they progress toward truly flexible and operationally supportable modular power architecture.					
15. SUBJECT TERMS Logistics; Flight operations; Space architecture; Multi-mission spacecraft; Space power; Solar array; Batteries; Fuel cells					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 40	19a. NAME OF RESPONSIBLE PERSON STI Help Desk (email: help@sti.nasa.gov)
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (include area code) 443-757-5802

